SAND2017-9709PE

Recent Developments in Laser Imaging Diagnostics for Studying Turbulence-Flame Interactions

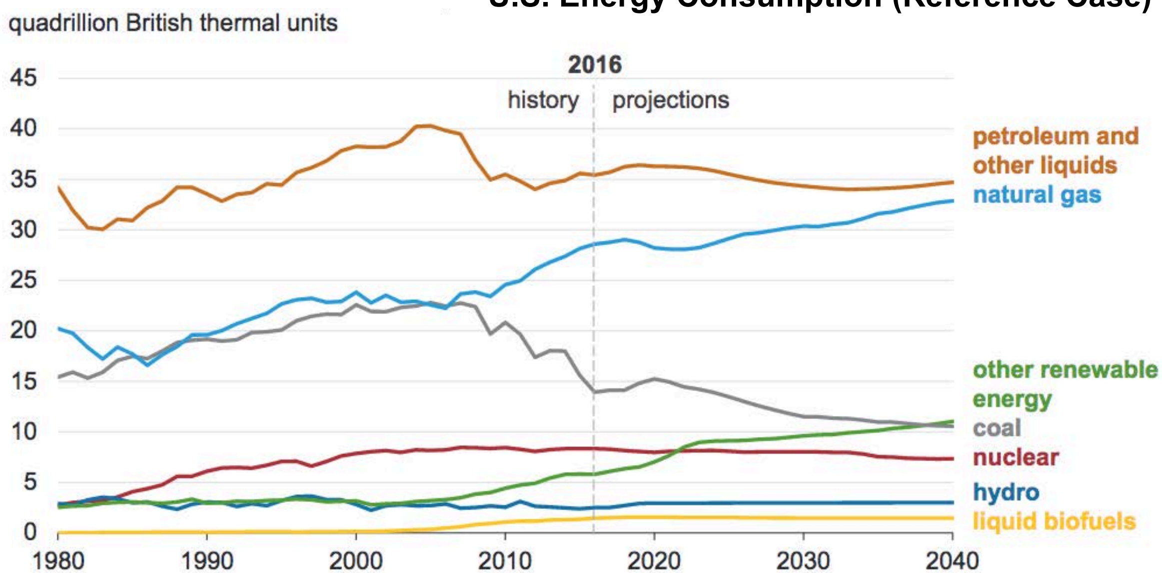
Jonathan Frank

Combustion Research Facility
Sandia National Laboratories
Livermore, CA

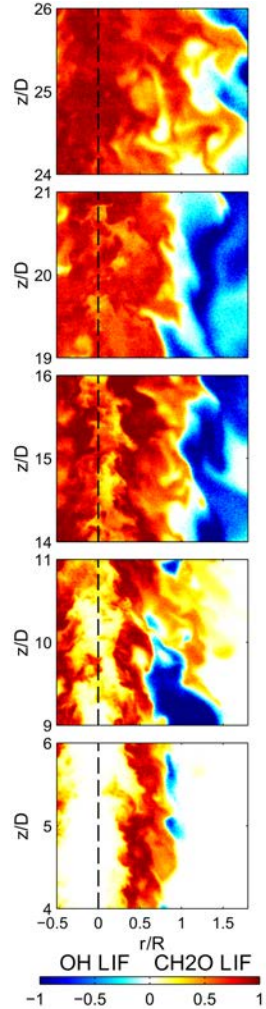
Motivation

- Fundamental understanding of interactions between turbulence and combustion chemistry
- Multi-dimensional, time-dependent, nonlinear problem
- Advancement of combustion theory and modeling
- Demand for hydrocarbon combustion for foreseeable future

U.S. Energy Consumption (Reference Case)

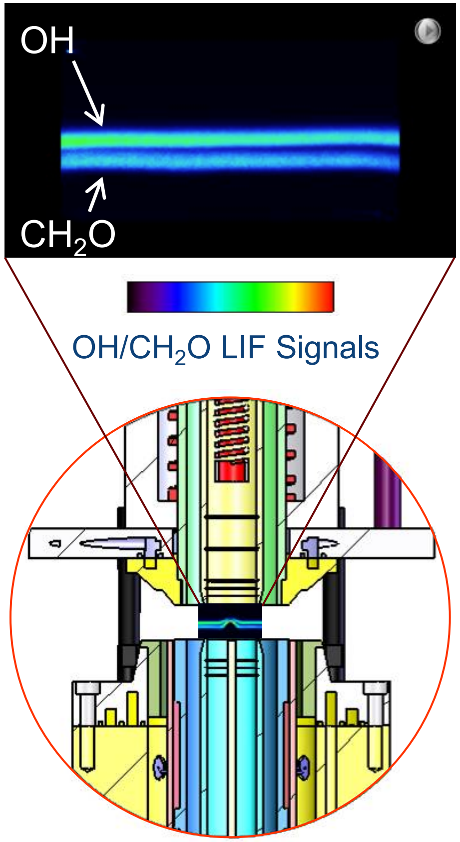


U.S. Energy Information Administration: Energy Outlook, Jan. 2017 (www.eia.gov/aeo)

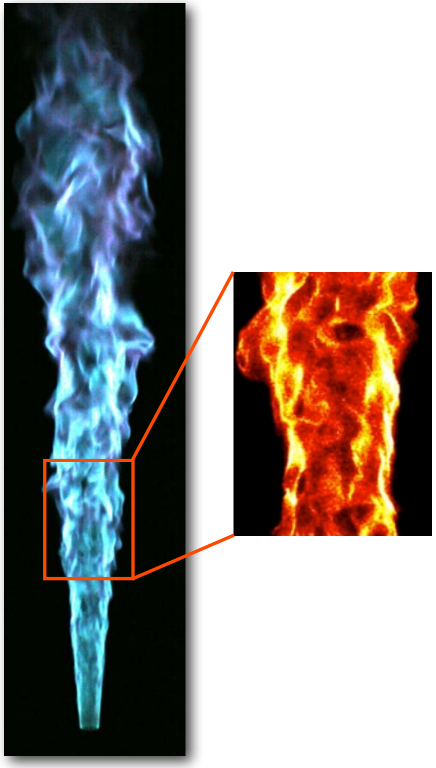


Approaches to Studying Flow-Flame Interactions

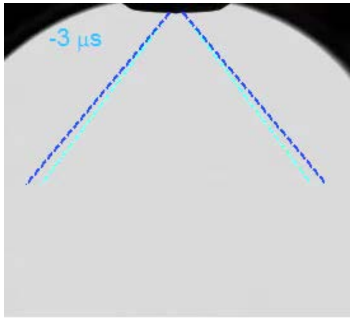
Isolated Repeatable Transient Flow-Flame Interactions

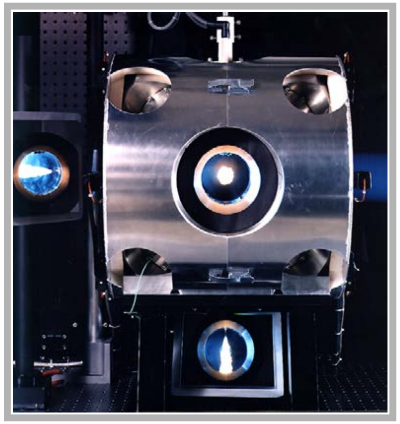


Turbulent Flows in Canonical Geometries

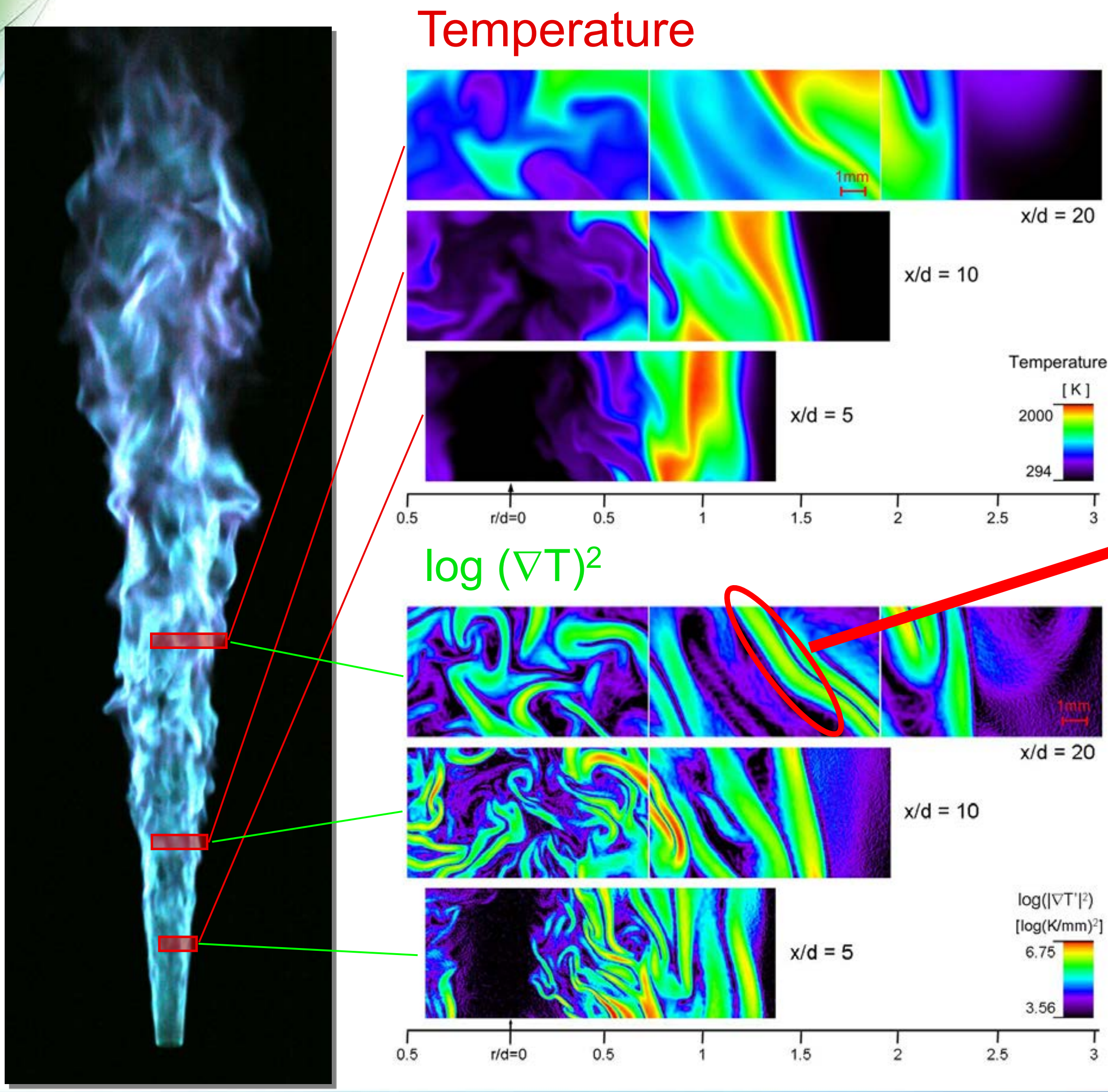


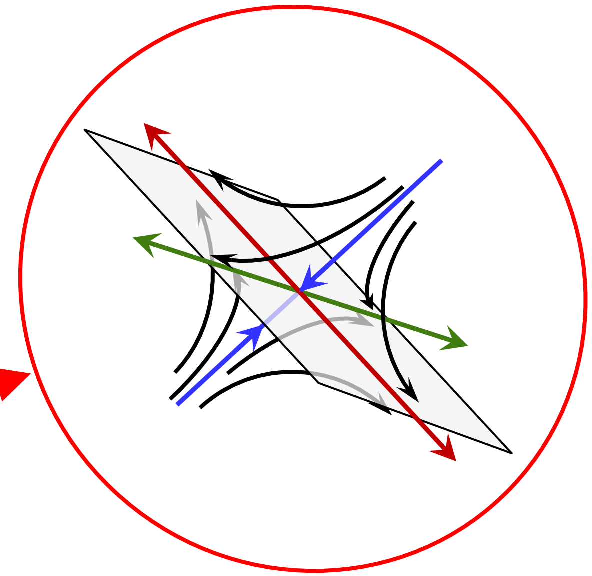
Challenging Environments





Structure of Turbulence Impacts Rates of Molecular Mixing





Feedback between turbulence and combustion

Requires measurements of fluid dynamics and thermochemical state

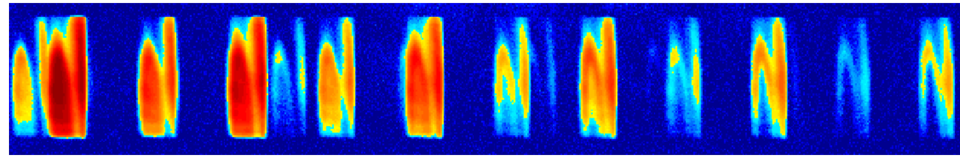
J. Frank, S. Kaiser *Exp. Fluids* 44:221 (2008)

Themes in Laser Imaging Diagnostics for Understanding Turbulence-Flame Interactions

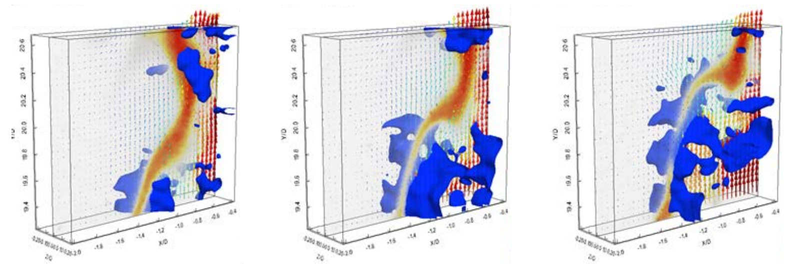
- Advances in dimensionality of diagnostics
  - Dynamics & structure of turbulence-chemistry interactions
    - velocity/species/temperature: 3D and 4D (spatio-temporal) measurements
  - Thermochemical state
    - temperature/species: single-point ➞ 1D ➞ 2D measurements
- Expanding capabilities in challenging environments
  - Approaches for treating interferences, imaging artifacts
  - Tailoring diagnostics to problem of interest
- Opportunities for coupling experiments and simulations
  - Approaches for statistical comparisons of multi-dimensional, multi-parameter datasets
  - Development and optimization of experimental and simulation methods

Outline

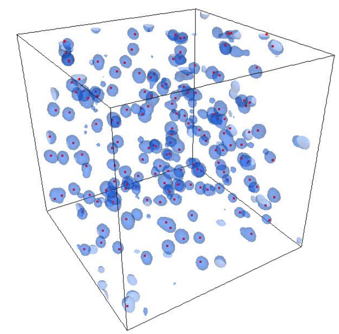
Advances in Temperature & Species Measurements



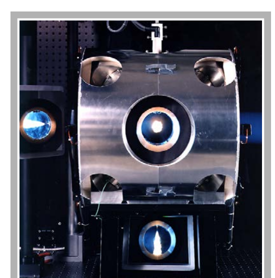
3-D Measurements of Flow Fields in Turbulent Flames

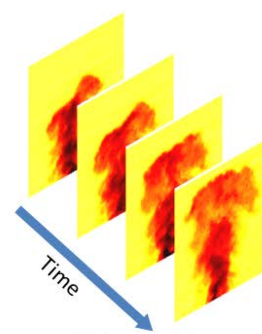


Coupling Tomo-PIV with Large Eddy Simulations



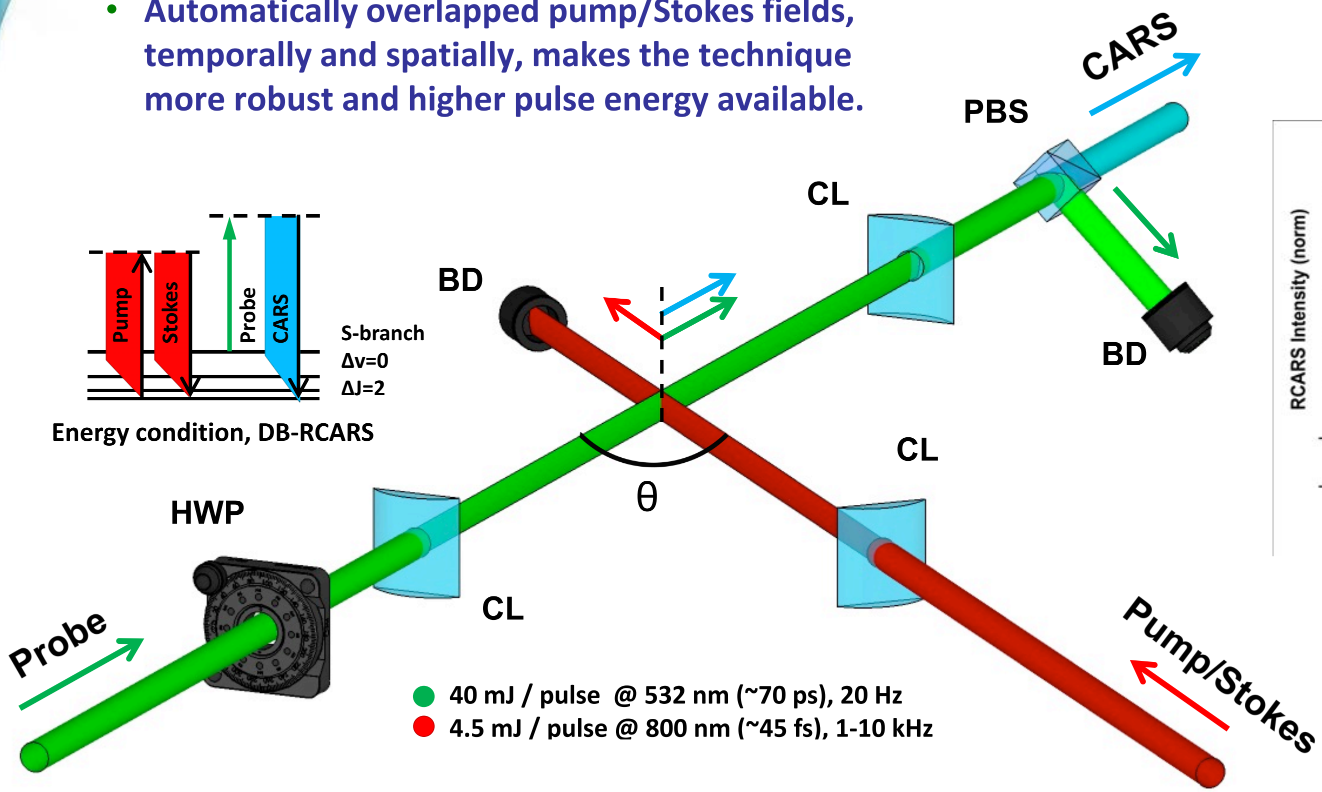
Dynamics of Transient Flows in Challenging Environments

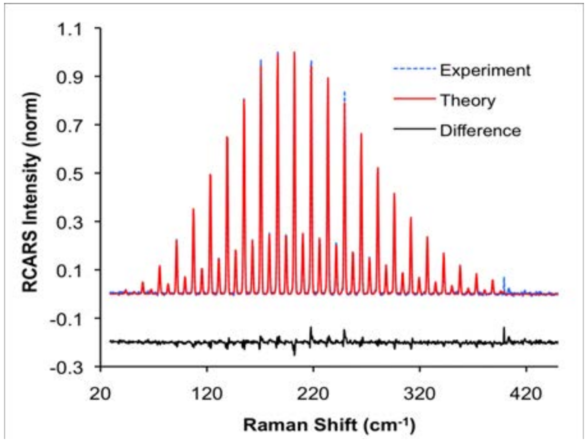




Two-Beam Phase Matching Scheme for hybrid fs/ps CARS Enables 1-D and 2-D Measurements

- Automatically overlapped pump/Stokes fields, temporally and spatially, makes the technique more robust and higher pulse energy available.



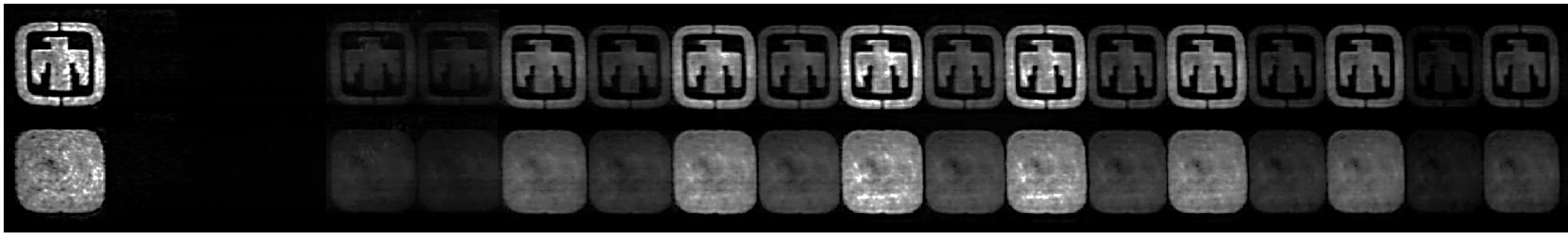


Rotational CARS spectrum of N_2 at 1800 K

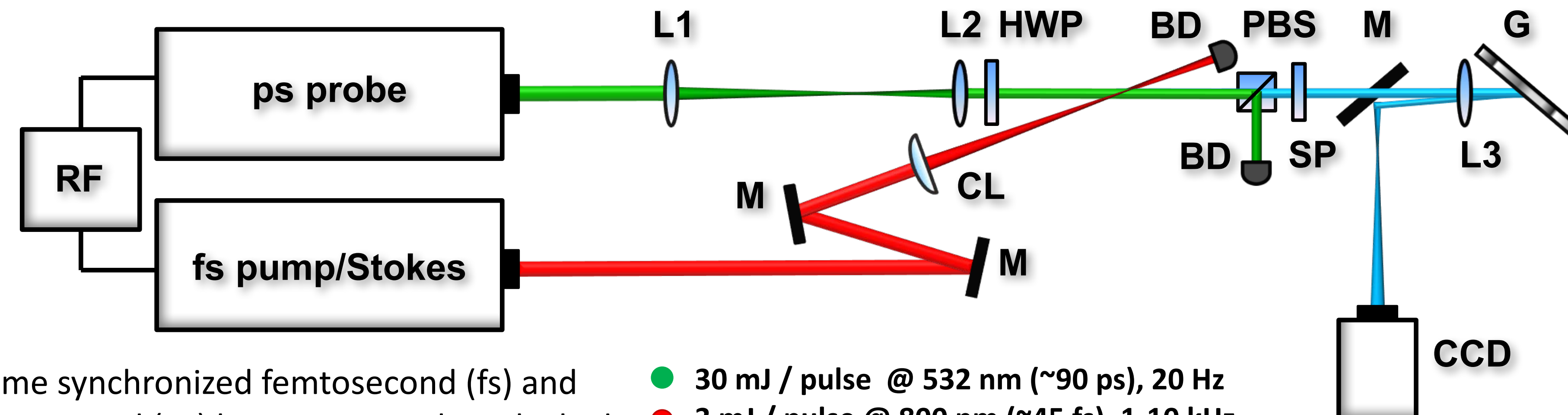
Courtesy of Chris Kliewer

Spectrally Resolved Detection of 2-D CARS

Rotational quantum number J = 4 5 6 7 8 9 10 11 12 13 14 15 16



120 X 125 pixels = 15000 spatially correlated spectra in a single laser shot.

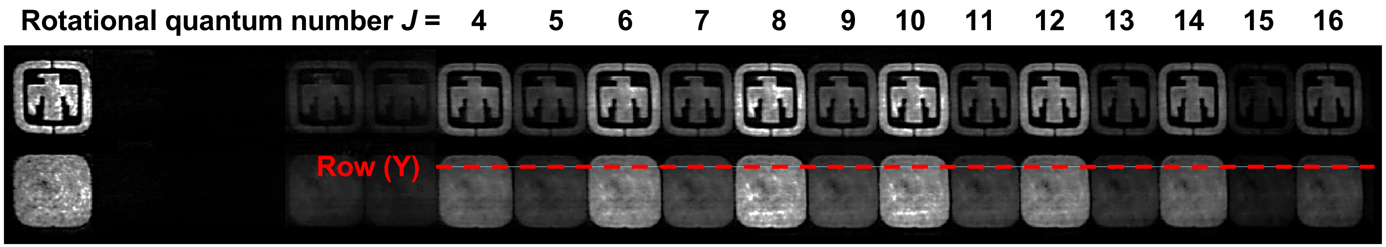


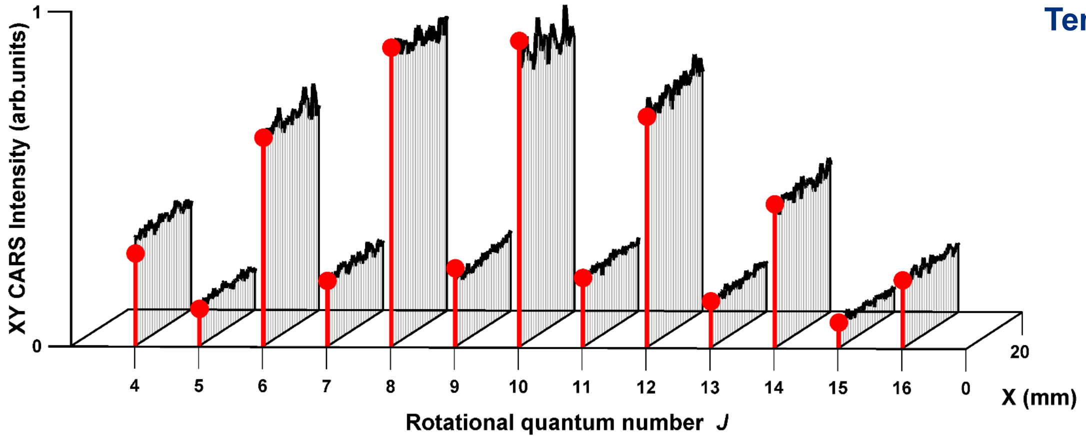
Time synchronized femtosecond (fs) and picosecond (ps) laser system, phase locked to an external 100 MHz RF source.

- 30 mJ / pulse @ 532 nm (~90 ps), 20 Hz
- 3 mJ / pulse @ 800 nm (~45 fs), 1-10 kHz

Bohlin, Kliewer, *J. Chem. Phys.* 138:221101 (2013)

Simultaneous Planar Imaging and Multiplexed Spectroscopy in a Single-Shot





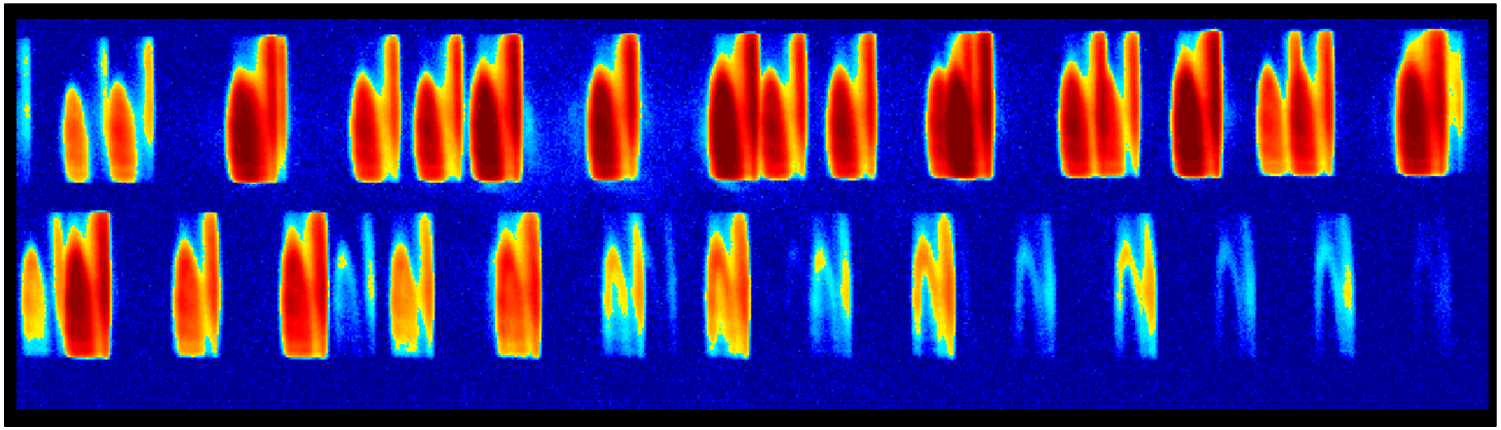
Temperature field statistics

Single row ~ 120 spectra
Average T = 299.6 K
Accuracy = 1.5 %

- Pixel-to-pixel extraction of spectra
- Insensitive to irregularities in probe & excitation pulses spatial profiles.

Enables Highly Accurate 2D Imaging Measurements of Temperature and Species

- Detecting 25 N_2 and 14 O_2 S-branch transitions with small spectral interference.

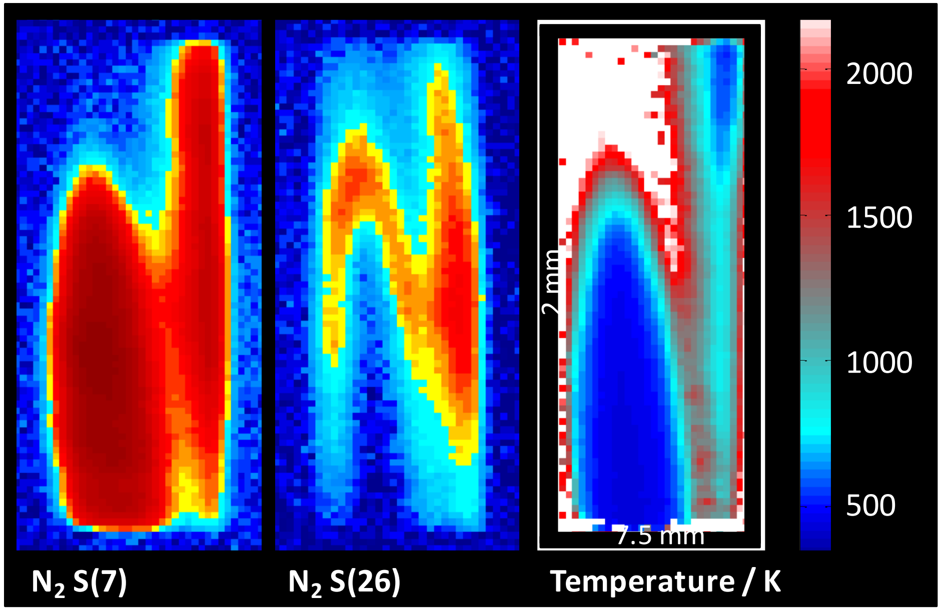


100 accumulated shots

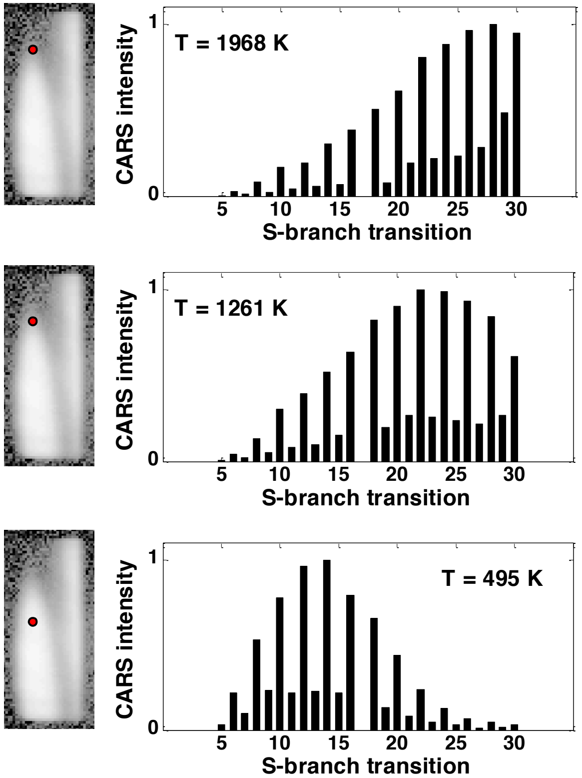
- Measurement configuration optimized for flame thermometry and detecting $[N_2]/[O_2]$, narrower mask, ~2100 spectra collected simultaneously, 2D-field of 2 x 7.5 mm.

Bohlin, Kliewer, *J. Phys. Chem. Lett.* *5*:1243 (2014)

Enables Highly Accurate 2D Imaging Measurements of Temperature and Species



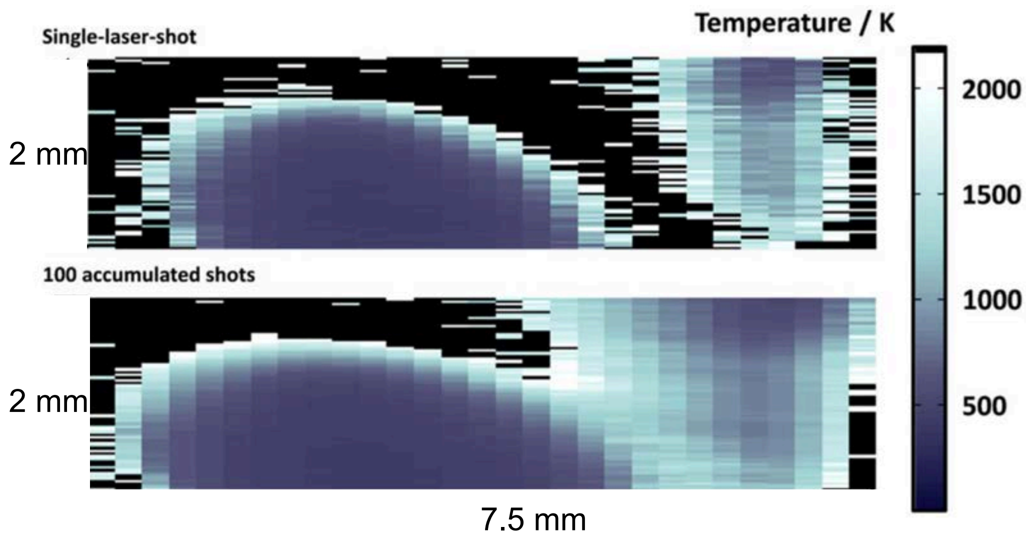
Spatial distribution of cold and hot N_2



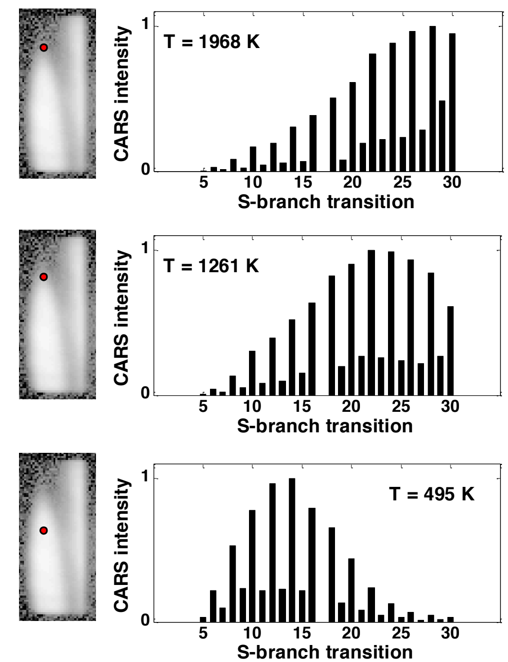
Rotational N_2 CARS spectra at 3 locations

Bohlin, Kliewer, *J. Phys. Chem. Lett.* *5*:1243 (2014)

Enables Highly Accurate 2D Imaging Measurements of Temperature and Species



Spatial distribution of cold and hot N_2 (lab coordinates)

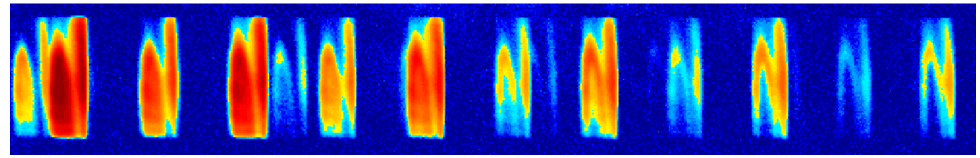


Rotational N_2 CARS spectra at 3 locations

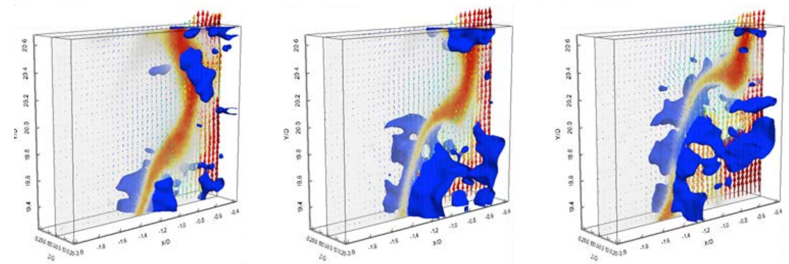
Bohlin, Kliewer, *J. Phys. Chem. Lett. 5*:1243 (2014)

Outline

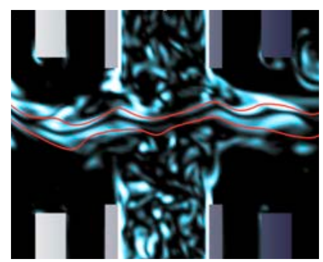
Advances in Temperature & Species Measurements

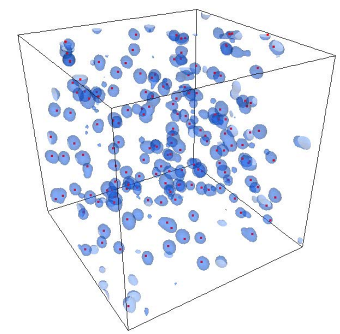


3-D Measurements of Flow Fields in Turbulent Flames

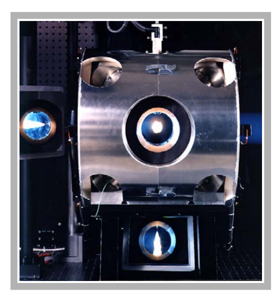


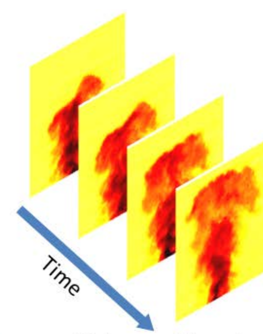
Coupling Tomo-PIV with Large Eddy Simulations





Dynamics of Transient Flows in Challenging Environments





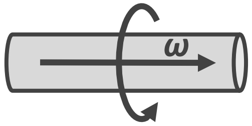
Measuring Structure of Turbulence
Tomographic Particle Imaging Velocimetry (PIV)

Tomographic Particle Image Velocimetry: 3-Component volumetric velocity measurements

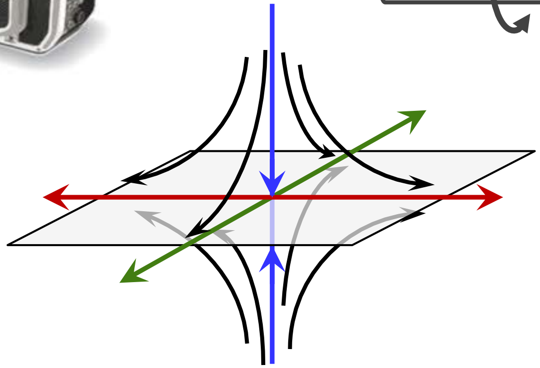
Key fluid dynamic quantities measured at multi-kHz rates

$$\boldsymbol{v} = u\hat{\imath} + v\hat{\jmath} + w\hat{k}$$

Velocity gradient tensor $\nabla\boldsymbol{v} = \frac{\partial u_i}{\partial x_j}$



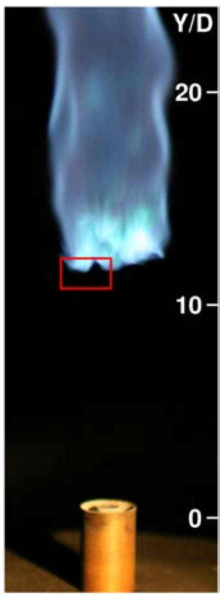
Vorticity $\boldsymbol{\omega} = \nabla\times\boldsymbol{v}$

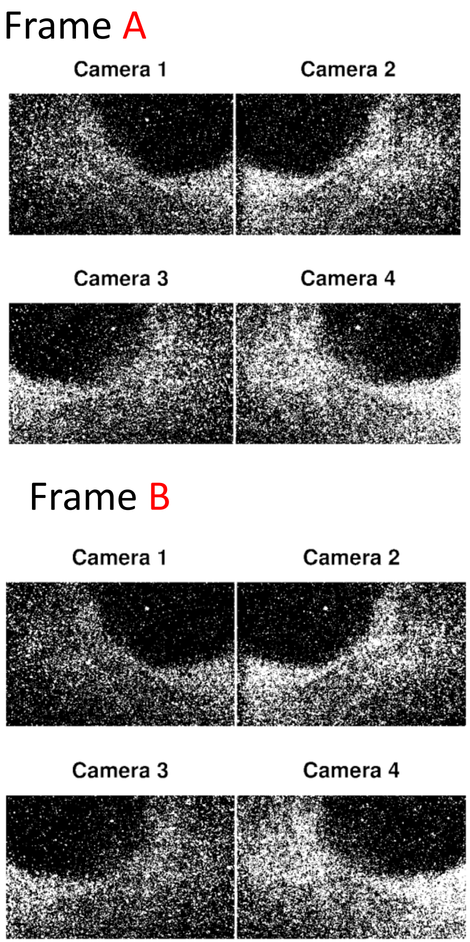


Strain rate tensor $S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$

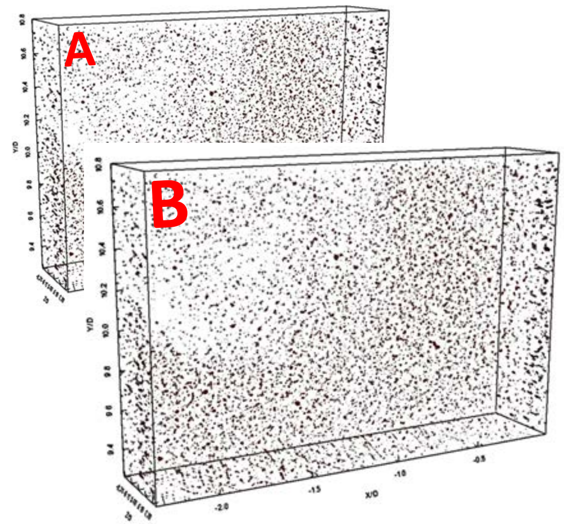
Measurements at multi-kHz rates

Tomo-PIV Data Acquisition and Processing

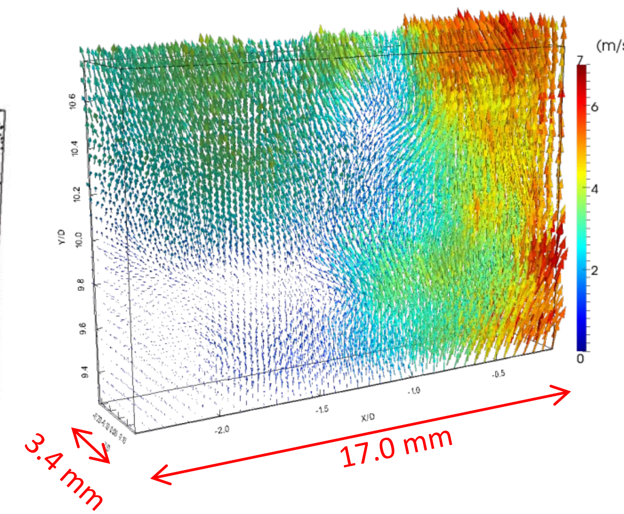




Data Acquisition



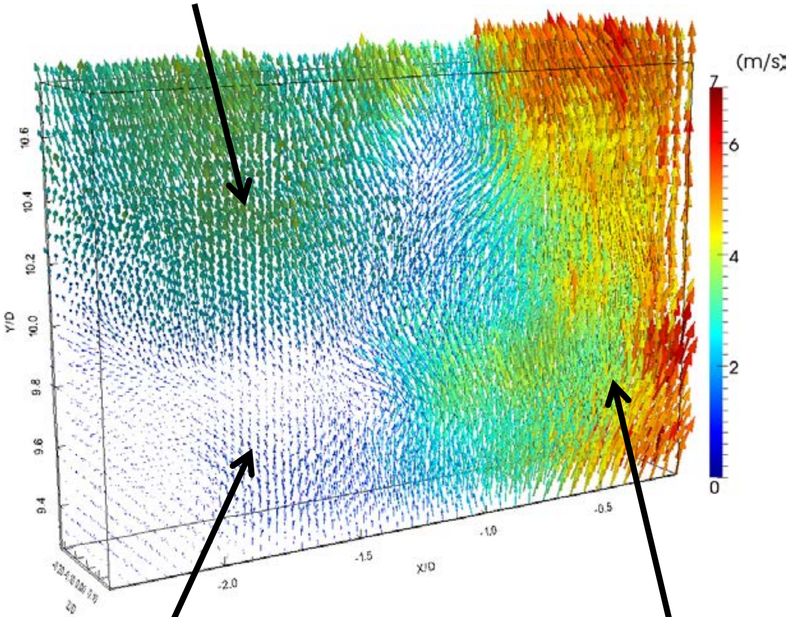
Probe Volume Reconstruction (multiplicative algebraic reconstruction tomography)



Volume Cross-Correlation to Calculate Particle Displacements

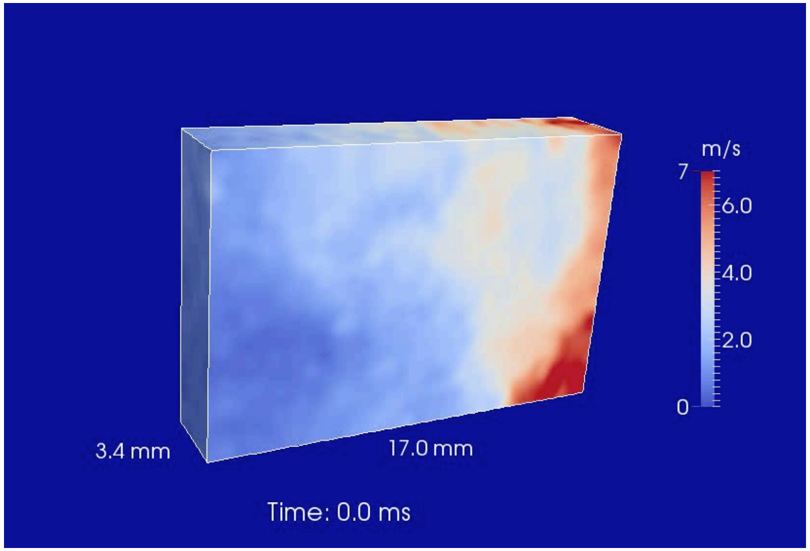
Tomo-PIV Data Processing
Volume Cross-Correlation

Flame products



Coflow stream

Jet flow



3D velocity field measured at 10 kHz

1 out of 64 vectors plotted

Volume per vector: 413 x 413 x 413μm^3
24 x 24 x 24 vx
with 75% overlap

Spatial and Temporal Resolution

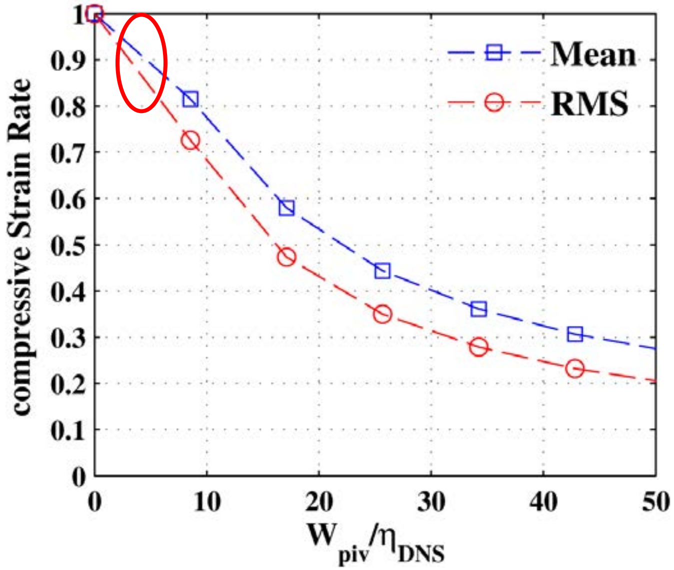
- **Lengthscales**
  - Probe volume dimensions: 16.5 x 12.3 x 2.5 mm^3
  - Spatial resolution: λ_m = 413 µm (width of interrogation volume)
  - Integral lengthscale: δ ~ 16 mm (full width at half max. of mean axial velocity)
  - Kolmogorov scale: η ~ 50 µm (*Air* jet) (Ref.: Frank and Kaiser, 2010)
    η ~ 120 µm (*Flame C*) (Ref.: Wang et al., 2007)

- **Timescales**
  - Measurement resolution: Δt_m = 0.1 ms (10 kHz)
  - Mean flow residence time: τ_{probe} ~ from 0.6 ms (*Flame C*) to 1.3 ms (*Air* jet)
  - λ_m-eddy turnover time: $\tau(\lambda_m) = (\lambda_m^2 . \delta)^{1/3}/u' \sim 0.7\ ms$
  - $\frac{\tau_{probe}}{\Delta t_m}$ ~ 6-13 (large scale dynamics resolved)
  - $\frac{\Delta t_m}{\tau(\lambda_m)}$ ~ 0.15 < 0.5 (Nyquist criterion satisfied)
  - $\frac{\tau_{probe}}{\tau(\lambda_m)}$ ~ 1-2 (λ_m-eddy turnover approximately completed in probe volume)

Issues with Tomographic Reconstruction

- Particle seed density
  - Balance seeding density for reactant/product regions
  - Tradeoff spatial resolution and probe volume
- Calibration of imaging system
  - Multiple target images + self-calibration technique
- Reconstruction algorithm
- Artifacts
  - Distortions in reconstructed particle images
  - "Ghost particles"

Effect of PIV Resolution on Measured Strain Rate



- Apply PIV windowing to DNS of forced isotropic turbulence[1]
- 10% average under-estimation of strain rate for $W_{piv} = 5\ \eta$

[1]DNS results from Johns Hopkins Turbulence Databases (turbulence.pha.jhu.edu)

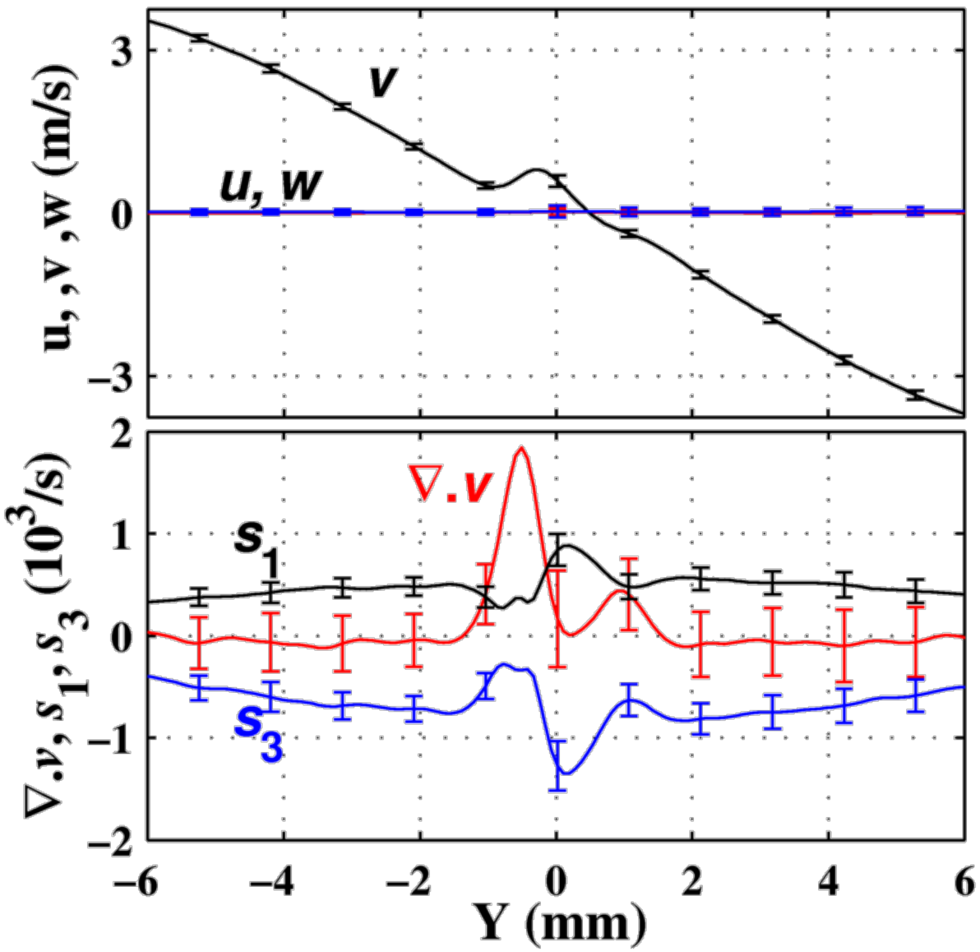
Measurement Uncertainty

Standard deviations

	Reactants	Flame
u	3 cm/s	7 cm/s
v (axial)	8 cm/s	12 cm/s
w	4 cm/s	8 cm/s

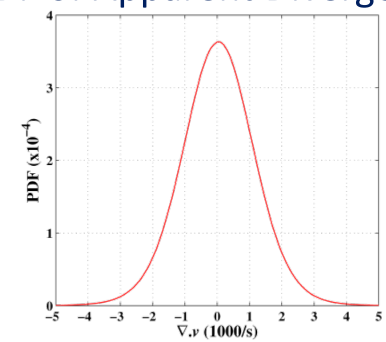
	Reactants	Flame
s_1	120 s^{-1}	160 s^{-1}
s_3	160 s^{-1}	250 s^{-1}
$\nabla . v$	350 s^{-1}	480 s^{-1}

Measurements in a laminar partially-premixed DME/Air opposed jet flame



Error bars = +/- standard deviation

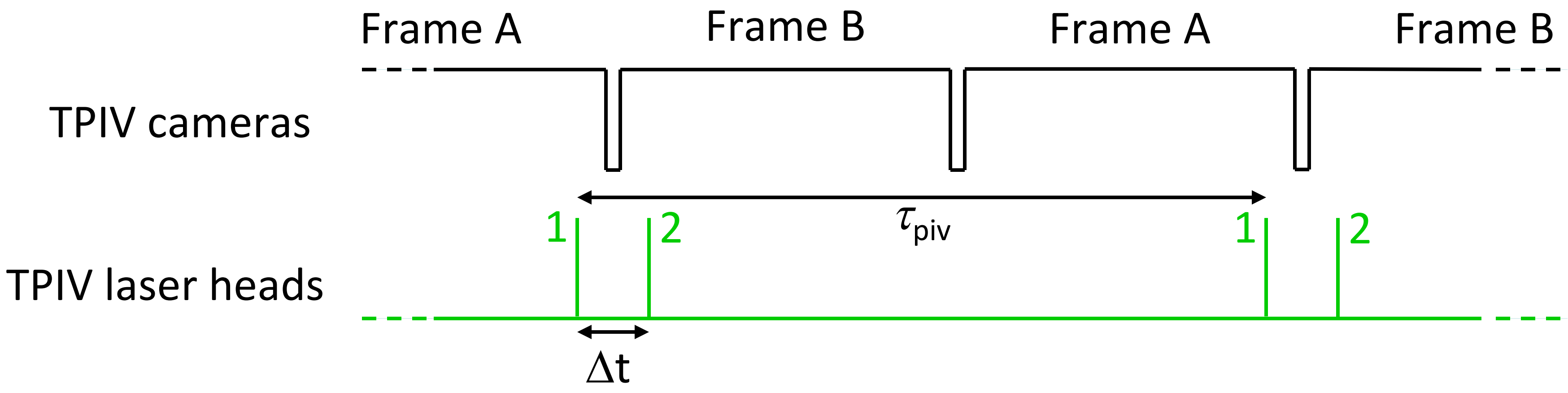
Tomo-PIV Measurement Uncertainty

Sources of errors *(estimate based on measurements in…)*	Velocity uncertainty	Derivative uncertainty
Noise, Thermophoretic diffusion, Volume reconstruction errors (*Laminar counterflow flame*)	1-10 cm/s	O(100) s^{-1}
Inherent spatial & temporal averaging of PIV, Apparent transport of ghost particles (*Turbulent Air jet*)	Max. uncertainty for unresolved eddies ~ 0.8 m/s	O(1,000) s^{-1} PDF of Apparent Divergence 
Beam steering (*Turbulent jet flame*)	< 1% for *v* < 5% for *u* and *w* *(Coriton et al., Exp. Fluids, 2014)*	< 1,000 s^{-1}

Temporal and Spatial Resolution Considerations

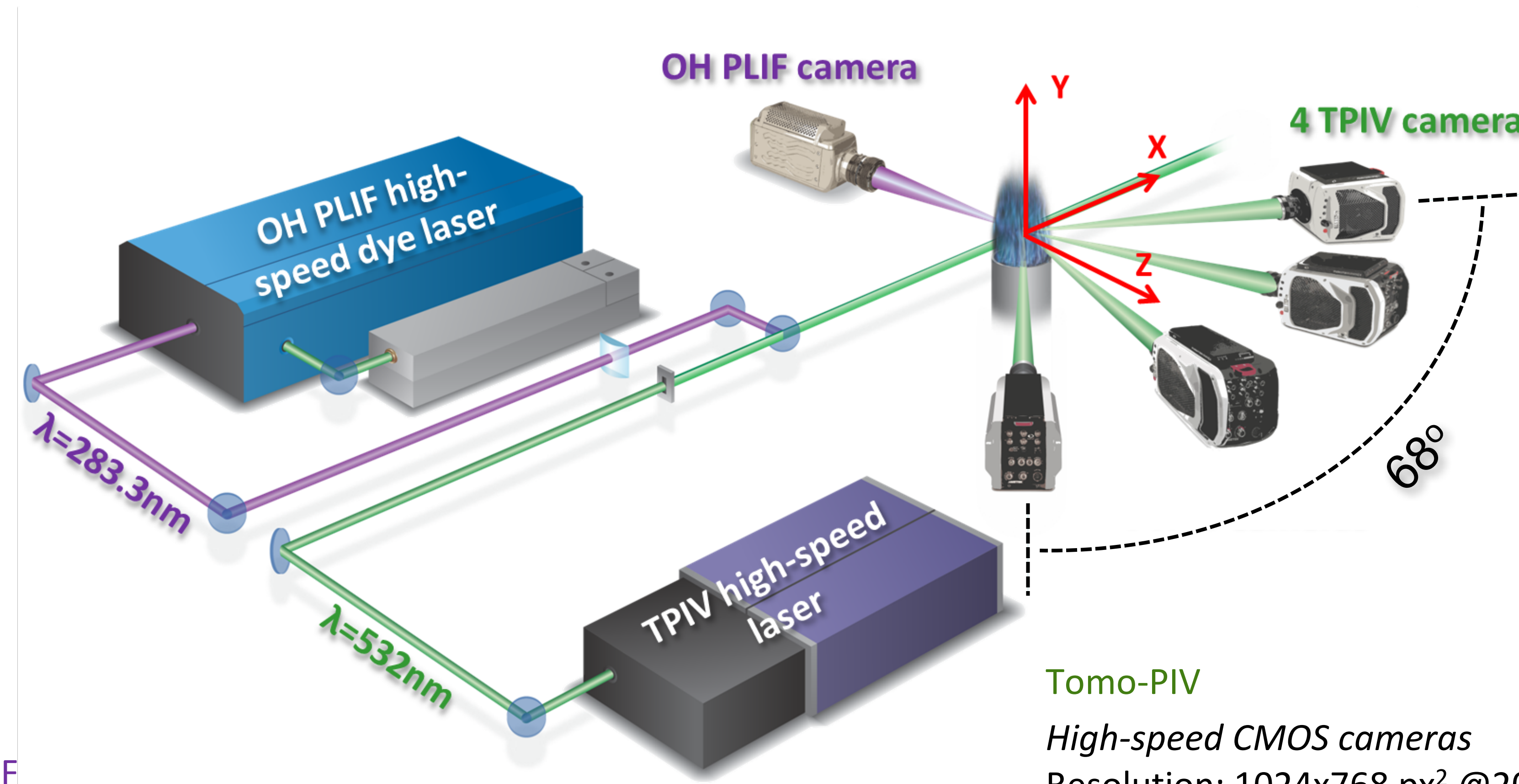
Resolved scales vs. turbulent flow scales

- PIV measurement resolution
  - Interrogation region: 360 x 360 x 360 μm^3 = 24 x 24 x 24 vx
  - f_{piv} = 10-16 kHz (τ_{piv} = 62.5-100 μs), Δt = 4-20 μs



- Finest scales of flow field in canonical burner geometries
  - Kolmogorov scales: $\eta_k \approx$ 10-100 μm $f_k \approx$ 5 kHz-100's kHz
  - $f_{Nyquist} = 2f_K$

Experimental Configuration
Tomographic PIV + OH LIF Imaging



OH LIF

Nd:YAG-pumped dye laser

E = 90 uJ/pulse @ 10 kHz

Tomo-PIV

High-speed CMOS cameras

Resolution: 1024x768 px^2 @20kHz

Dual-Head Nd:YAG laser

Each Head: 50W @ 10-40 kHz

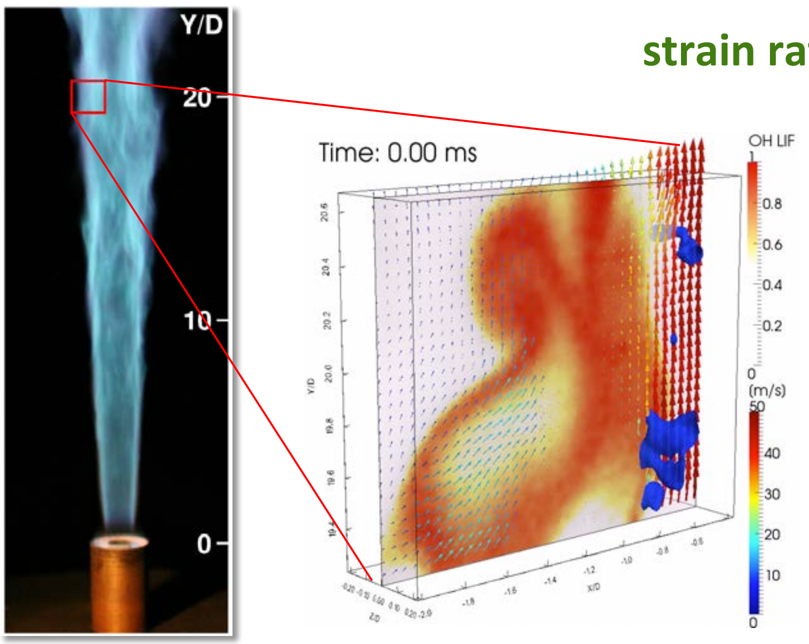
Interaction of Chemical Heat Release with Fundamental Processes in Turbulence

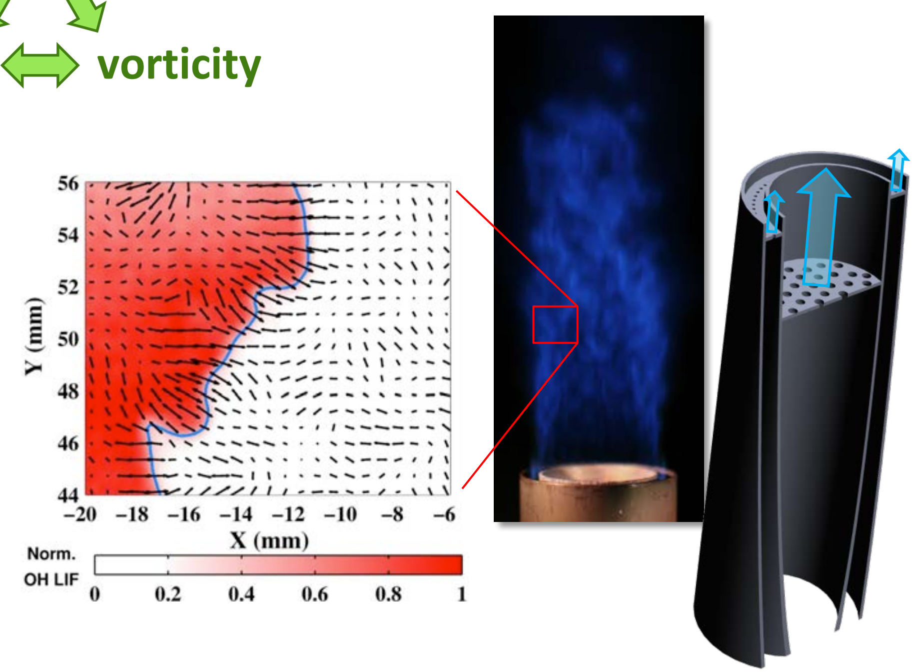
Partially-premixed flame with high mean shear, local extinction

heat release rate

strain rate ⟺ **vorticity**

Premixed flame with high dilatation, low mean shear

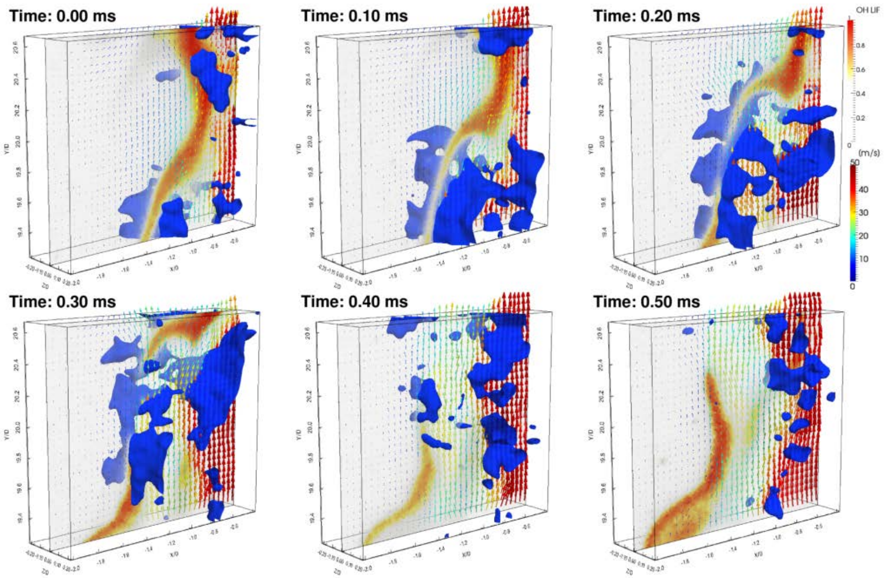


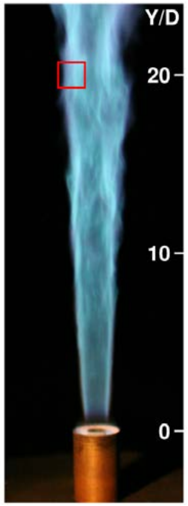


Tomographic PIV and OH PLIF at 10 kHz

Time Evolution of Strain Rate Induced Extinction

Tomographic PIV and OH PLIF at 10 kHz

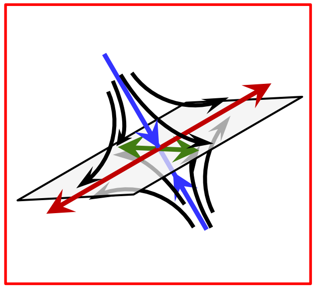




DME/air
Re=29,300

Blue isosurfaces: $s_3 = -15{,}000\ s^{-1}$

- High strain rate events are rare
- Time history of interaction is critical
- Preferred orientation of principal extensive strain rate in the shear layer of jets and jet flames



$s_1 > s_2 > s_3$

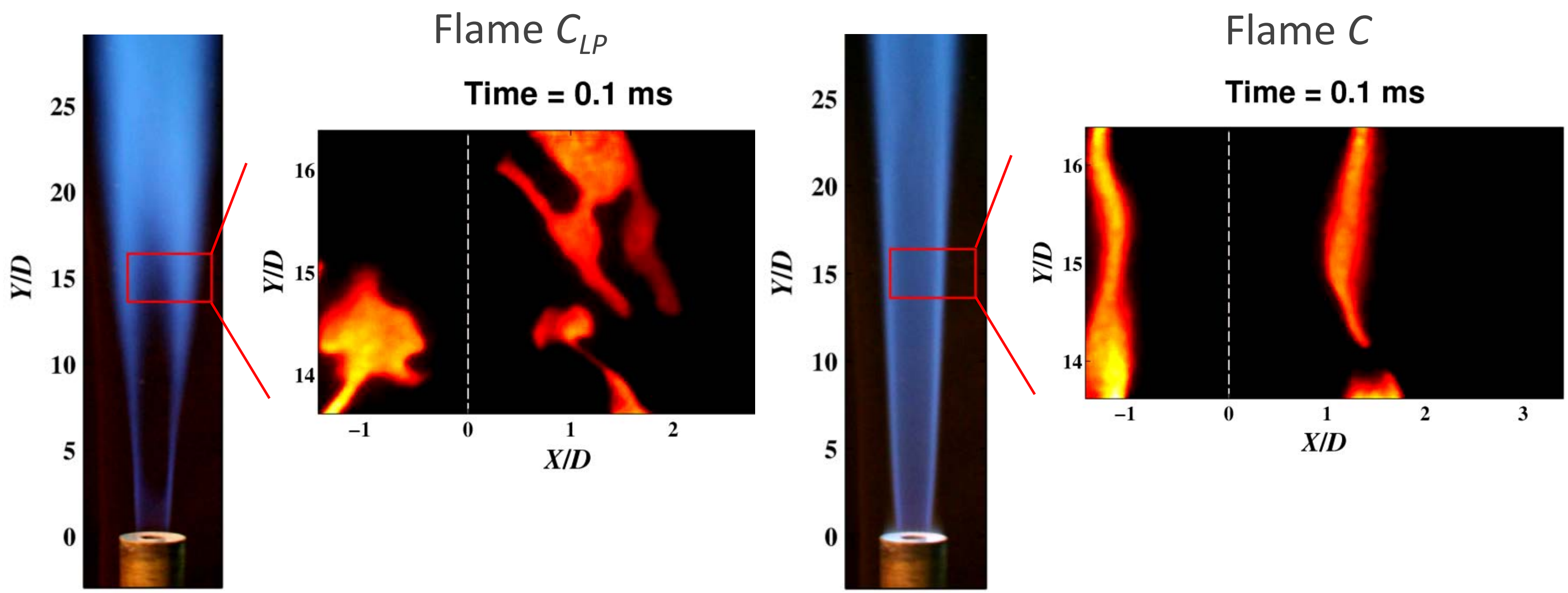
extensive int compressive

Steady laminar extinction limit: 817 s^{-1} (Zhou); 933 s^{-1} (Kaiser)

Coriton, Steinberg, Frank, *Exp. Fluids* 55:1 (2014)

Partially Premixed CH_4/Air Jet Flames with Different Amounts of Extinction
10 kHz OH LIF Imaging

Increasing Heat Release →

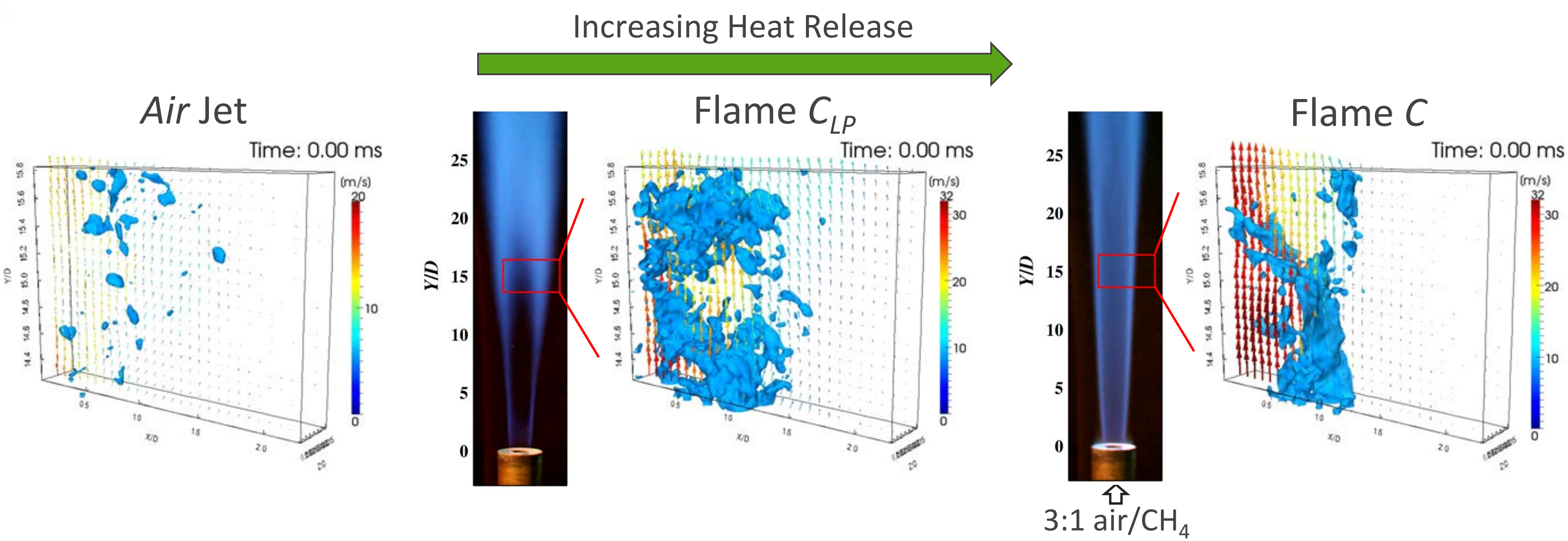


Summary of flow conditions.

Cases	φ_{jet}	Re_{jet}	V_{jet} (m/s)	V_{Pilot} (m/s)
Air	0.0	13500	27.5	0.0
C_{LP}	6.0	13000	27.5	1.8
C	6.0	13000	27.5	6.8

B. Coriton, A. Steinberg, J. Frank, *Exp. Fluids* 55:1 (2014)

Partially Premixed CH_4/Air Jet Flames with Different Amounts of Extinction
10 kHz OH LIF Imaging



Isosurfaces: $|s_{thrs}| = 7{,}000\ s^{-1}$

$|s| = (s_1^2+s_2^2+s_3^2)^{1/2}$

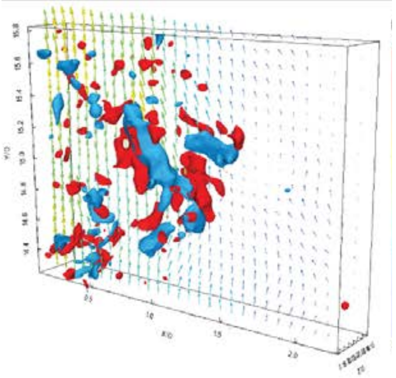
- Bursts of large strain rate structures
- Air Jet: small fragmented structures throughout jet
- Flame C: large elongated structures concentrated near reaction zone
- Flame C_{LP}: localized extinction → intermittent features of both non-reacting and reacting flows

Coriton, Steinberg, Frank, *Exp. Fluids* 55:1 (2014)

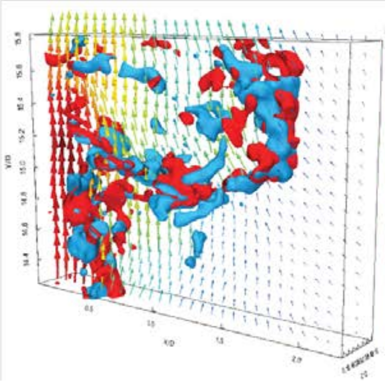
Enhanced Coupling of Strain Rate and Vorticity

Increasing Heat Release

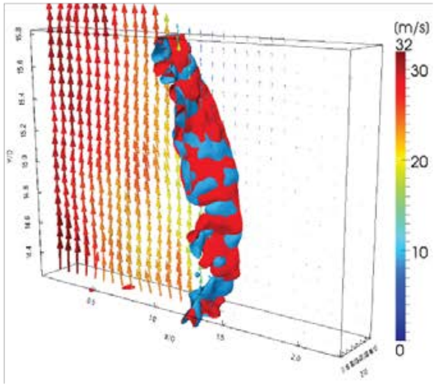
Air Jet



Flame C_{LP}



Flame *C*

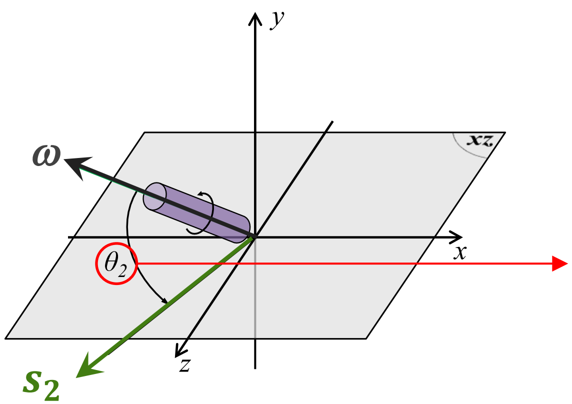


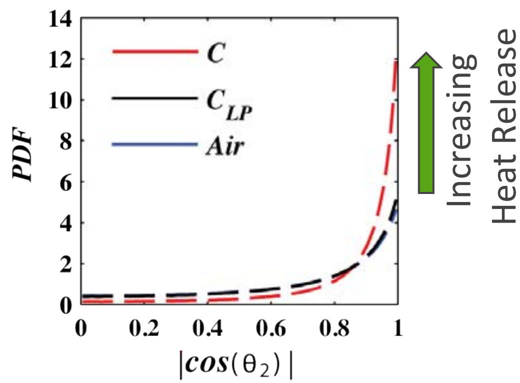
Strain Rate Isosurfaces

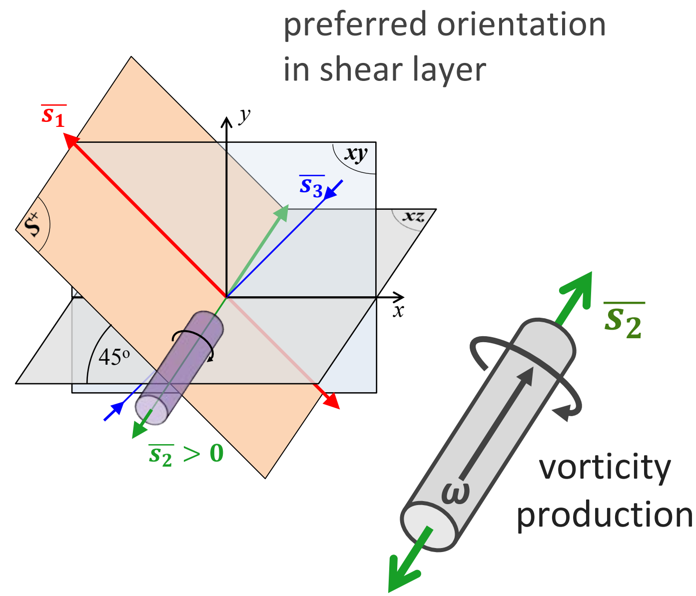
Vorticity Isosurfaces

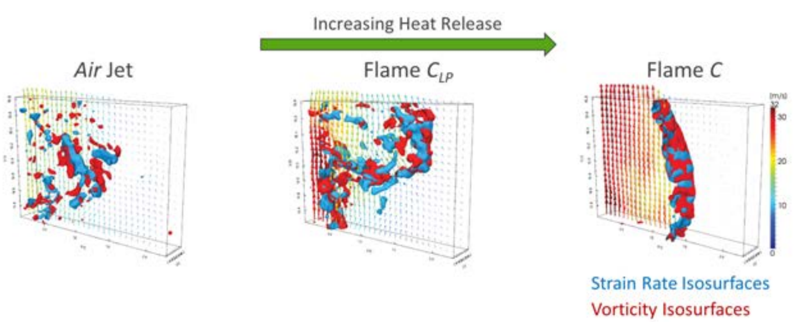
Coriton, Frank, *Physics of Fluids* 28:025109 (2016)

Preferential Vorticity Alignment with Extensive Strain Increases Vorticity Production







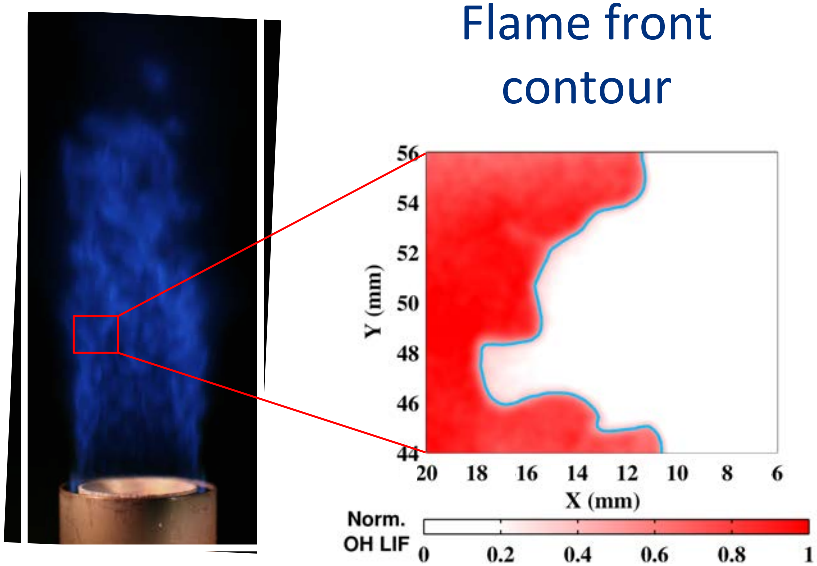


- **Heat release induces alignment of vorticity and s_2 strain**
- **Large vorticity preferentially aligned with mean extensive $\overline{s_2}$ strain**

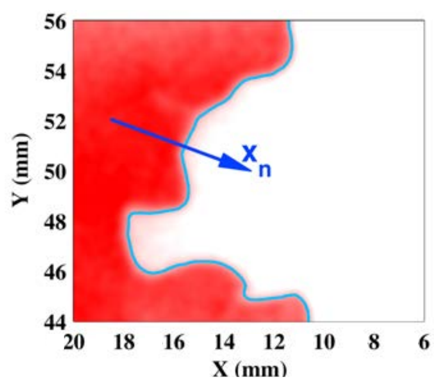
Coriton, Frank, *Physics of Fluids* 28:025109 (2016)

Premixed Flame
Flame Front and Strain Rate Analysis

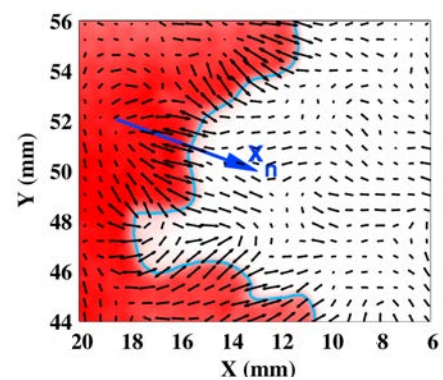
Flame front contour



Flame front normal

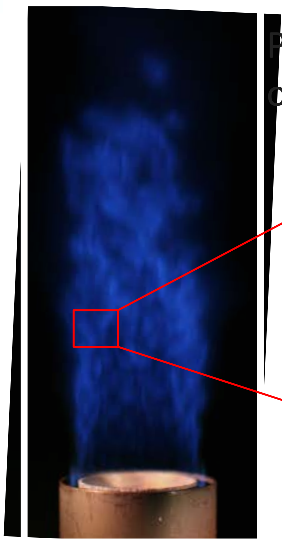


Strain rate eigenvectors

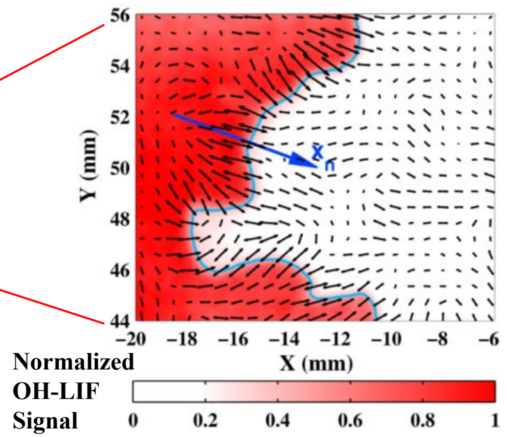


Strain-rate statistics analyzed from 5,000 single-shot TPIV measurements

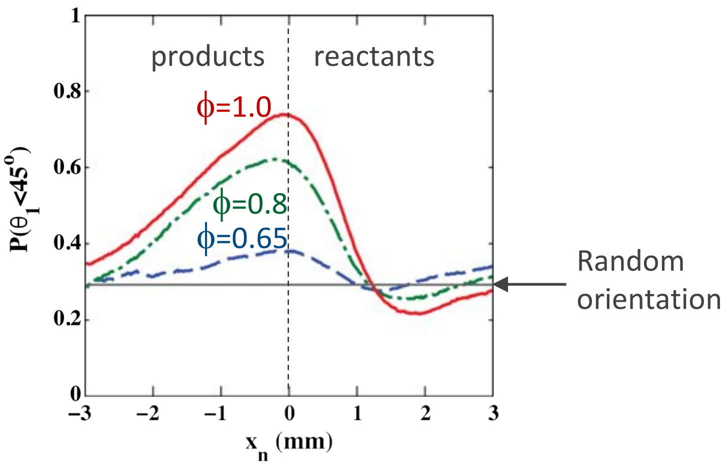
Premixed Flame
Effect of Dilatation on Strain Rate Alignment



Projection of extensive strain (s_1) onto plane of OH-LIF measurement



Probability of extensive strain (s_1) alignment towards flame-front normal direction



φ	τ	S_L (m/s)	u'/S_L	Da_t
0.65	4.8	0.15	4.1	1.7
0.80	5.8	0.24	2.6	3.0
1.00	6.5	0.34	1.8	5.1

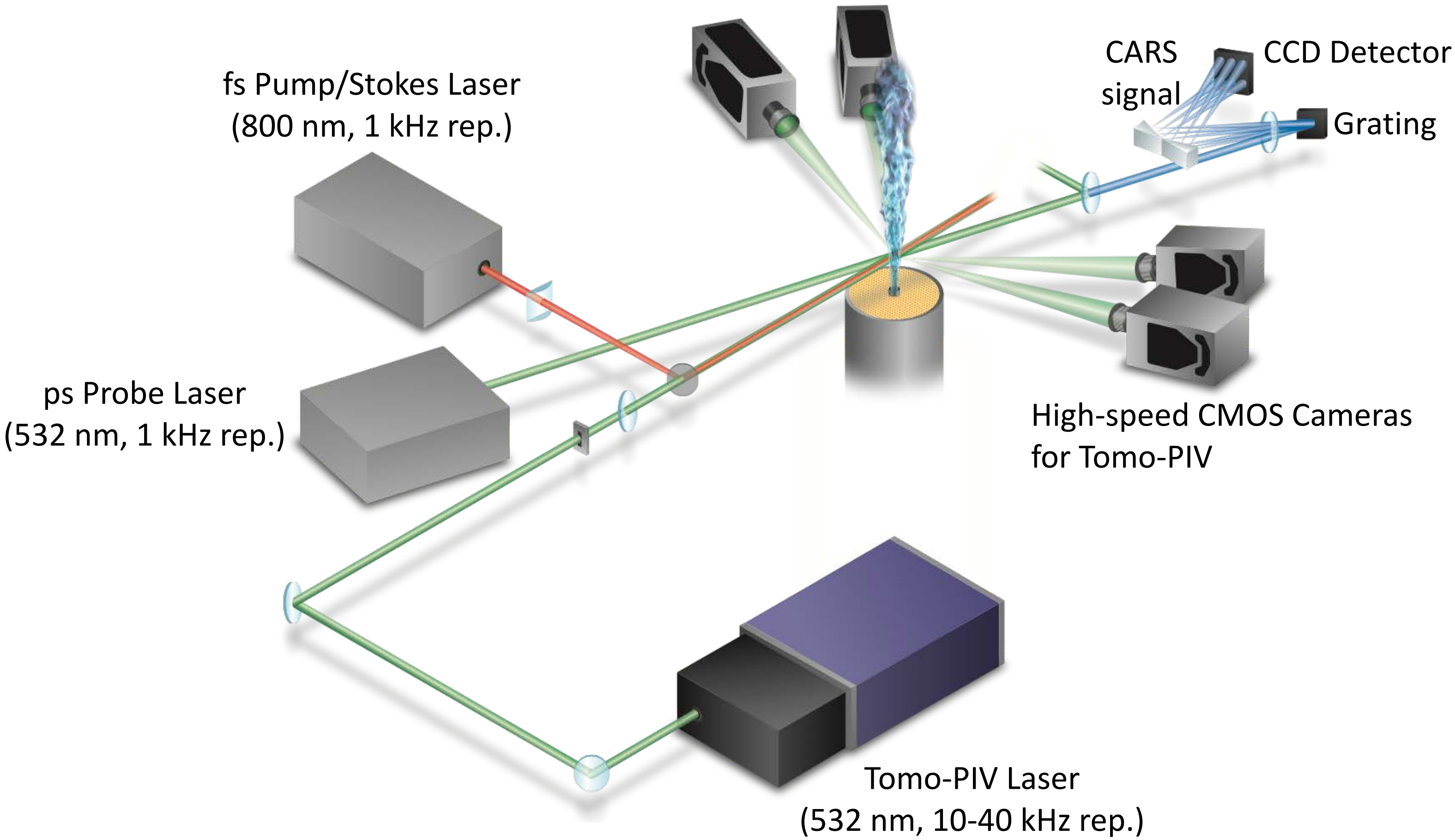
$$\tau = (T_b - T_u)/T_u$$

$$Da_t = (l/u')/(l_F/S_L)$$

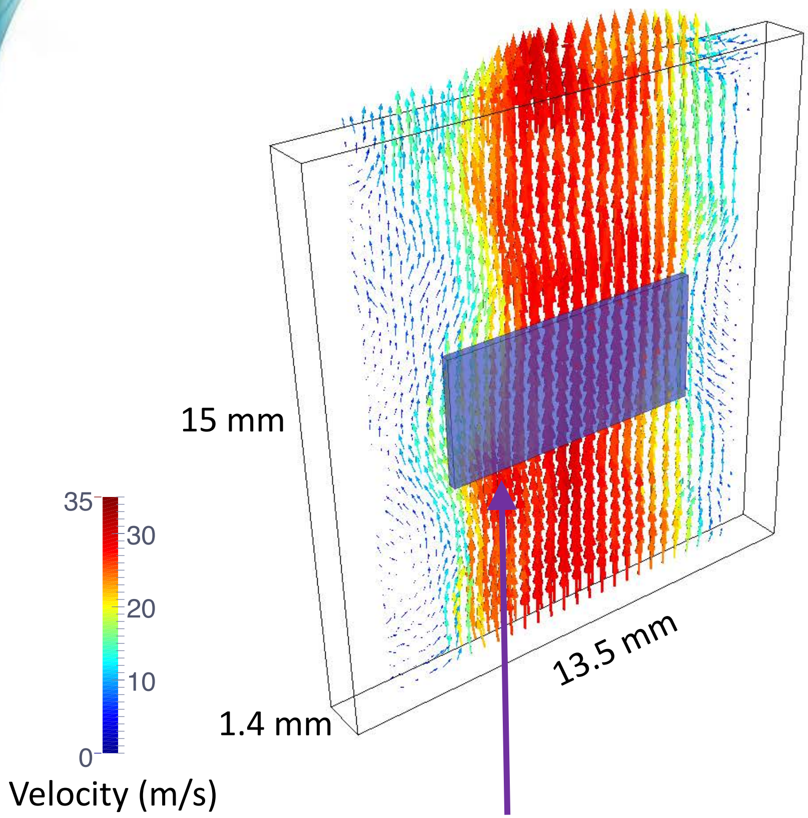
- **Extensive strain rate preferentially aligned with flame-front normal**
- **Localized to millimeter length scale**
- **Strongly dependent on turbulence-flame parameters**

Coriton & Frank, *Proc. Combust. Inst.* 36:1885 (2017)

Work in Progress
Simultaneous Tomo-PIV and 2D-CARS for Velocity-Temperature Imaging



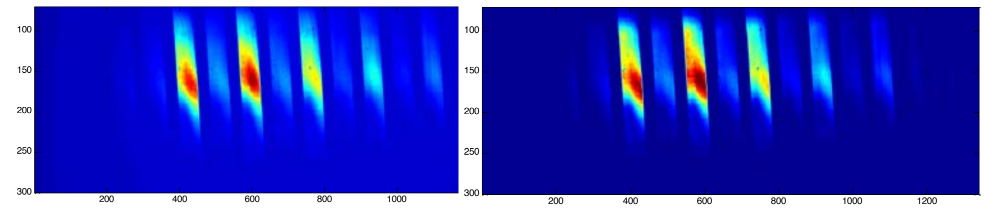
Feasibility of Combining 2D-CARS and PIV Demonstrated in Isothermal Nitrogen Jet



CARS Measurement Region

6.7 mm x 3.5 mm

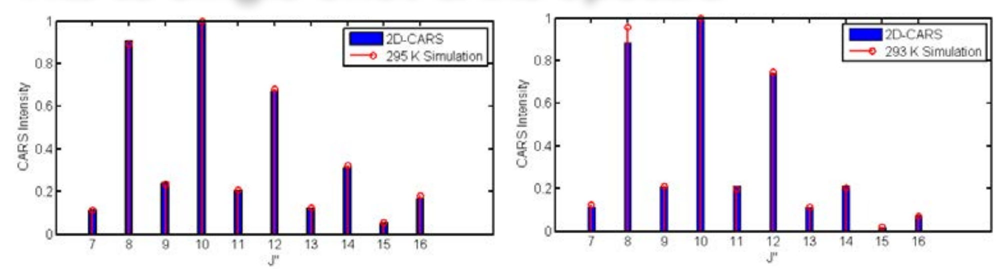
2D-CARS Signals



No Particles

With PIV Particles

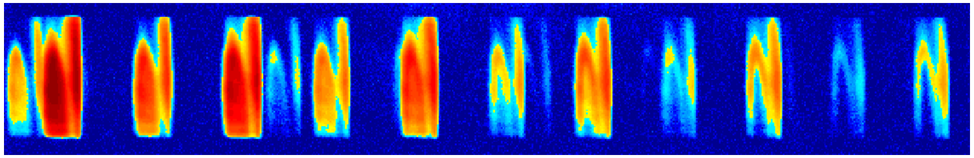
Fits to Single-Shot CARS Spectra



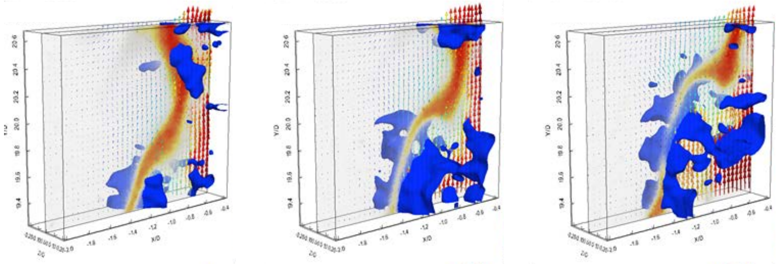
CARS Measurements Unaffected by PIV Particles

Outline

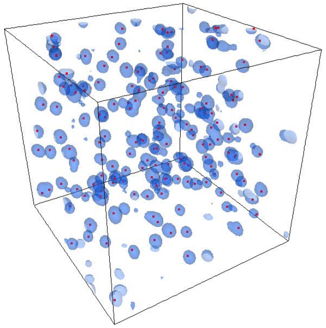
Advances in Temperature & Species Measurements



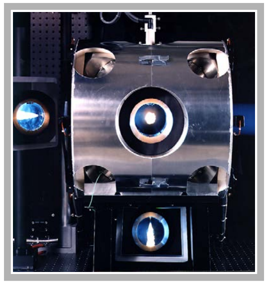
3-D Measurements of Flow Fields in Turbulent Flames

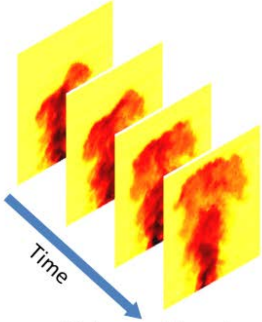


Coupling Tomo-PIV with Large Eddy Simulations



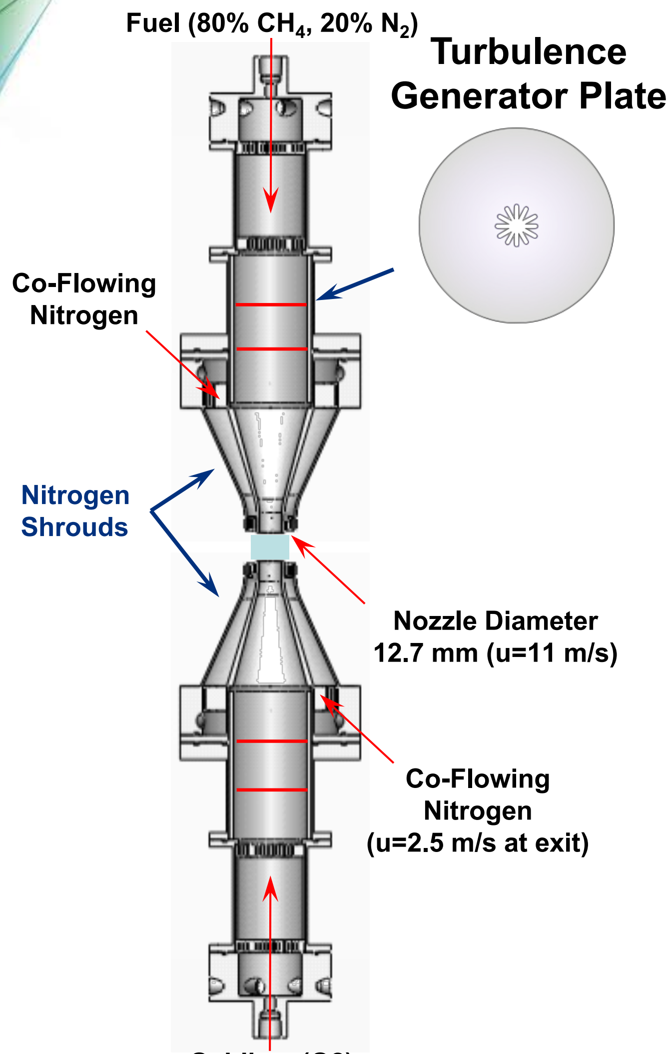
Dynamics of Transient Flows in Challenging Environments



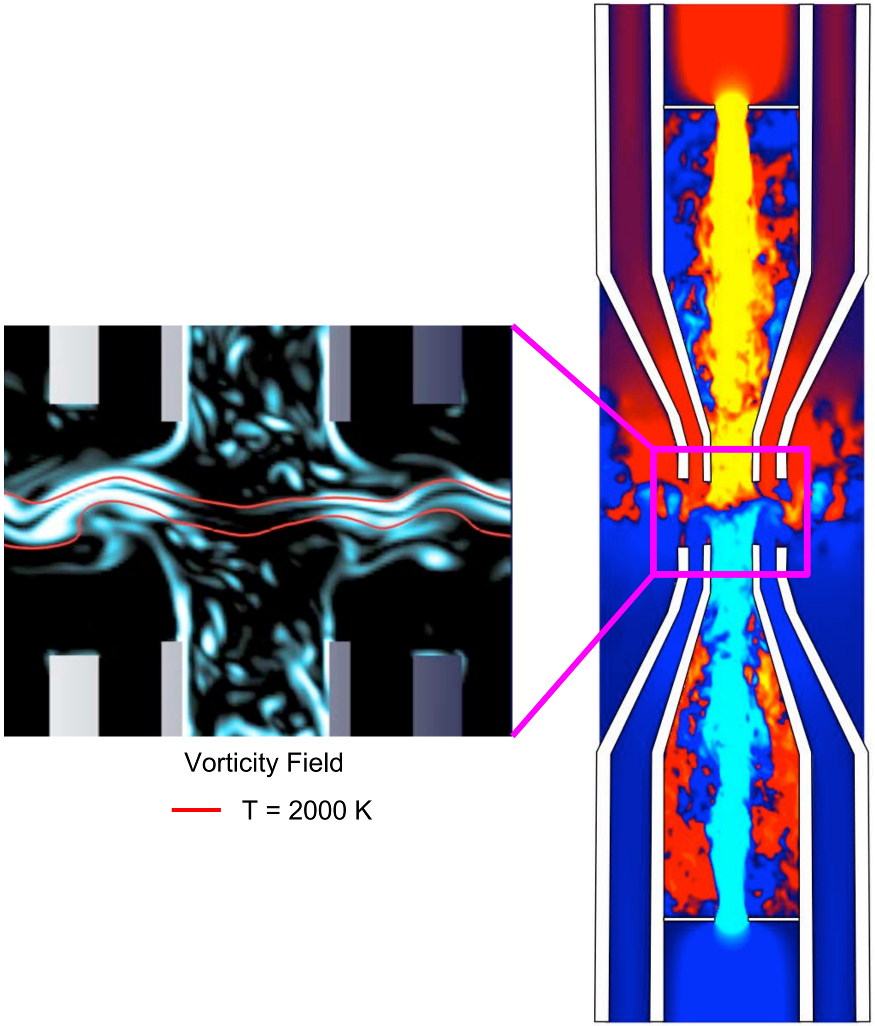


Coupling Experiments and Simulations

Requires detailed simulation of actual experimental configuration and sufficient run times for converged statistics



Coppola, Coriton, Gomez, *Combust. Flame 156 (2009)*



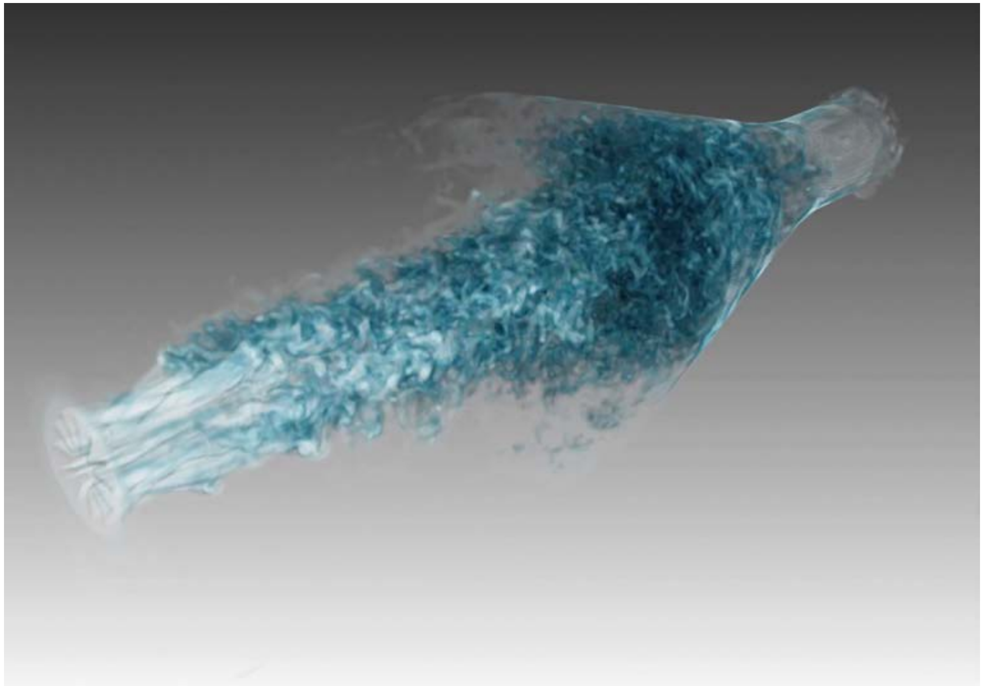
LES Calculations by Joe Oefelein

Theoretical-Numerical Framework
(RAPTOR: A general solver optimized for LES)

- **Theoretical framework … (Comprehensive physics)**
  - Fully-coupled, compressible conservation equations
  - Real-fluid equation of state (high-pressure phenomena)
  - Detailed thermodynamics, transport and chemistry
  - Multiphase flow, spray
  - Dynamic SGS modeling (<u>No Tuned Constants</u>)
- **Numerical framework … (High-quality numerics)**
  - Staggered finite-volume differencing (non-dissipative, discretely conservative)
  - Dual-time stepping with generalized preconditioning (all-Mach-number formulation)
  - Detailed treatment of geometry, wall phenomena, transient BC's
- **Massively-parallel … (Highly-scalable)**
  - Demonstrated performance on full hierarchy of HPC platforms

Oefelein *Prog. Aerosp. Sci. 42:2 (2006)*

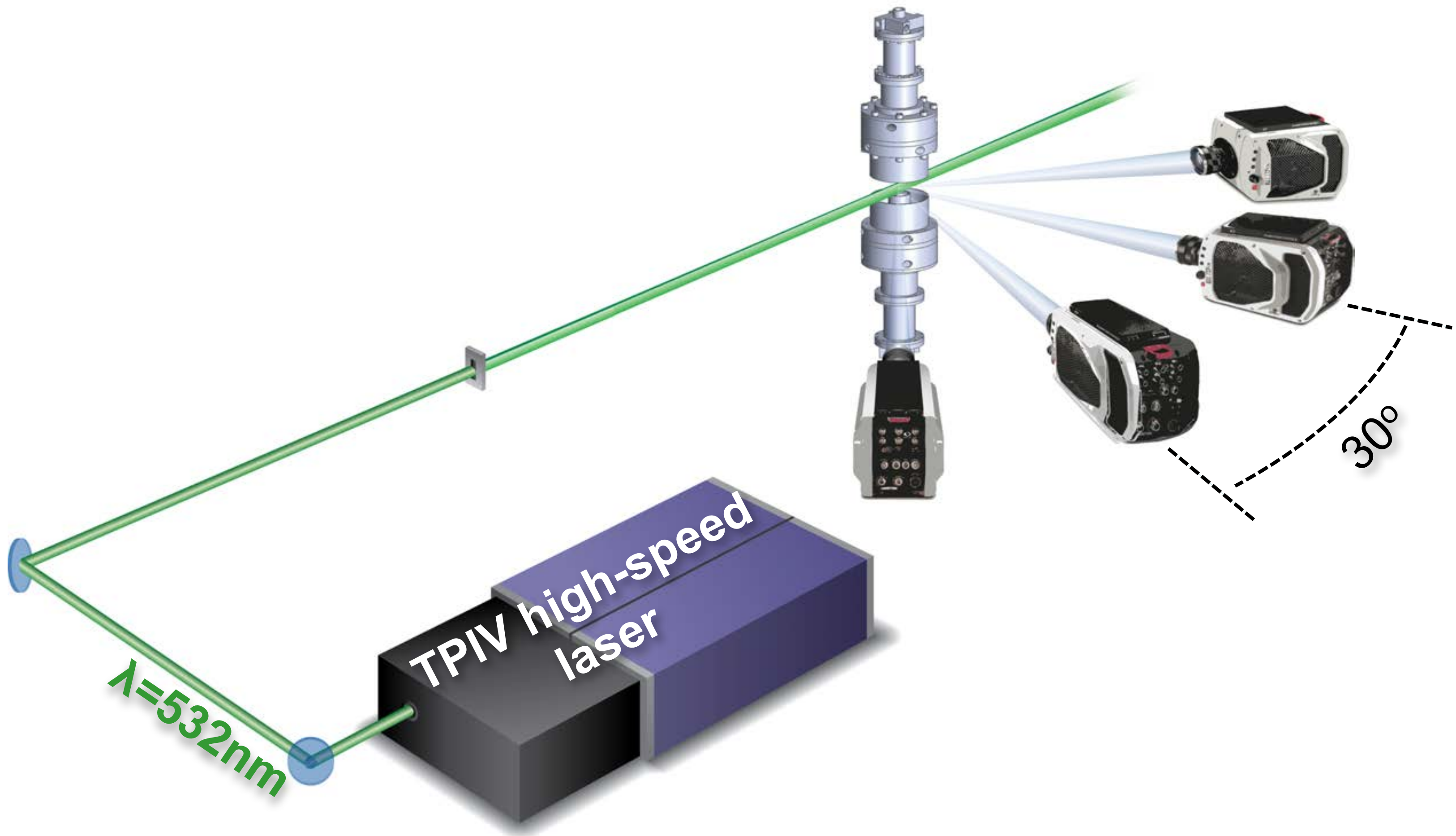
Full LES Domain Simulates Internal Flow Through Turbulence Generator Plate



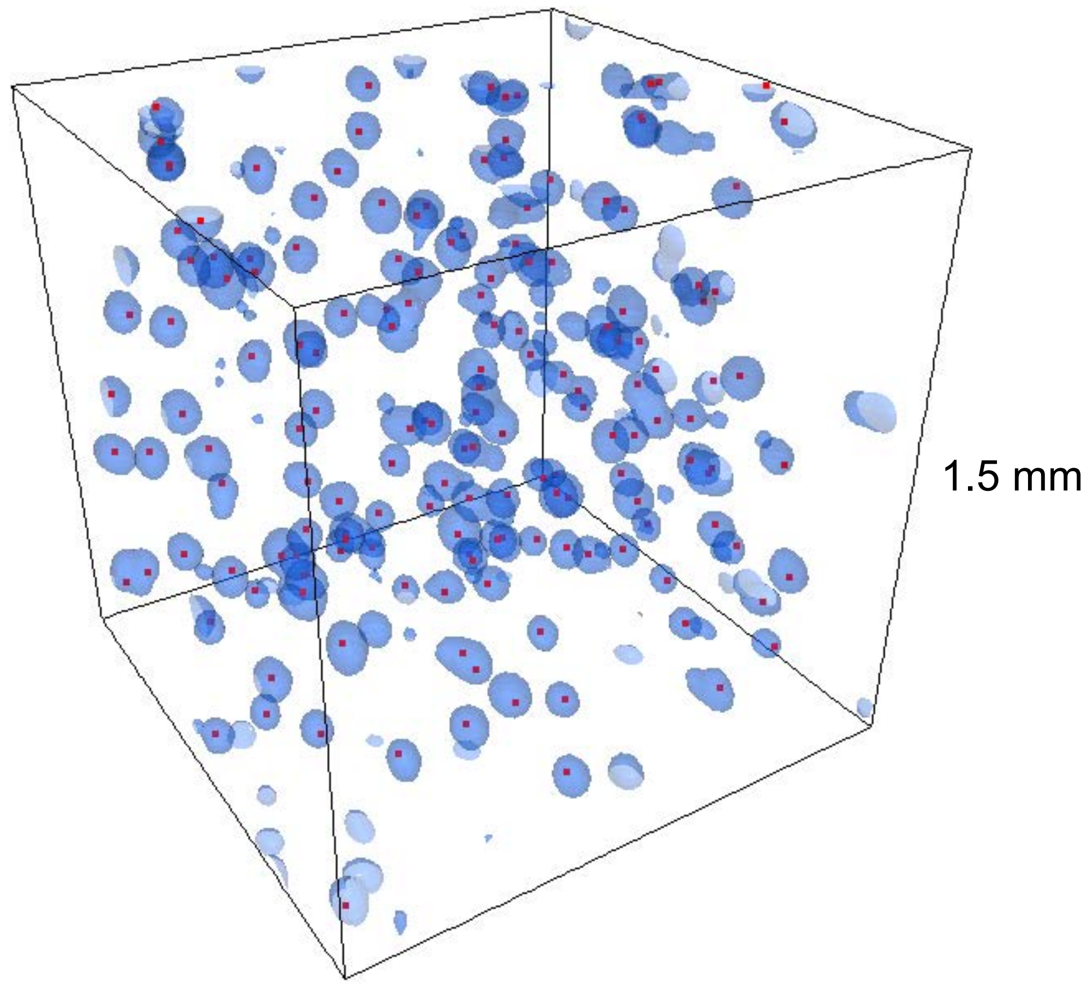
$|\omega|^2$ (s^{-2})

10^3  10^8

Emulate Experimental Configuration with Synthetic Tomographic Projections



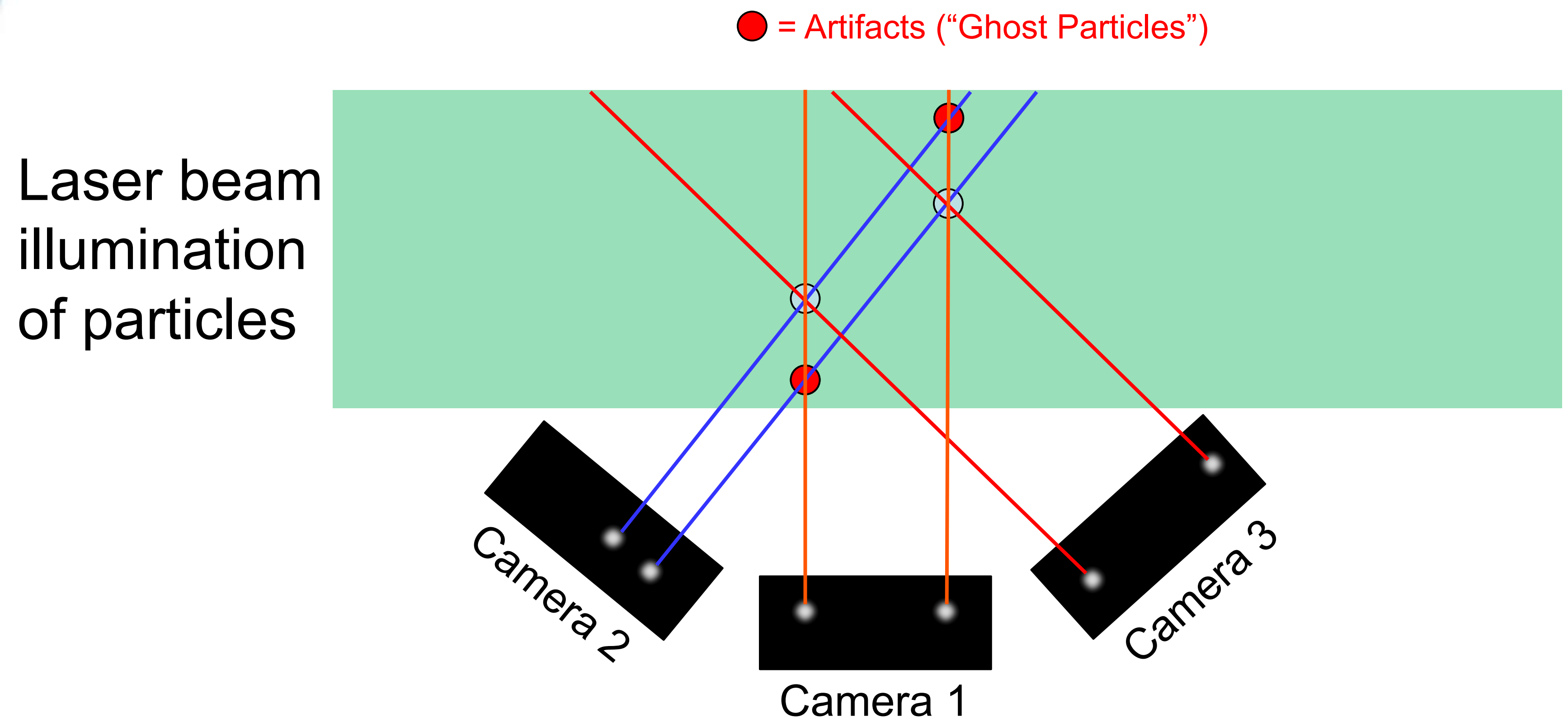
Subset of Reconstructed Particle Field



Red dots = actual particle locations from LES

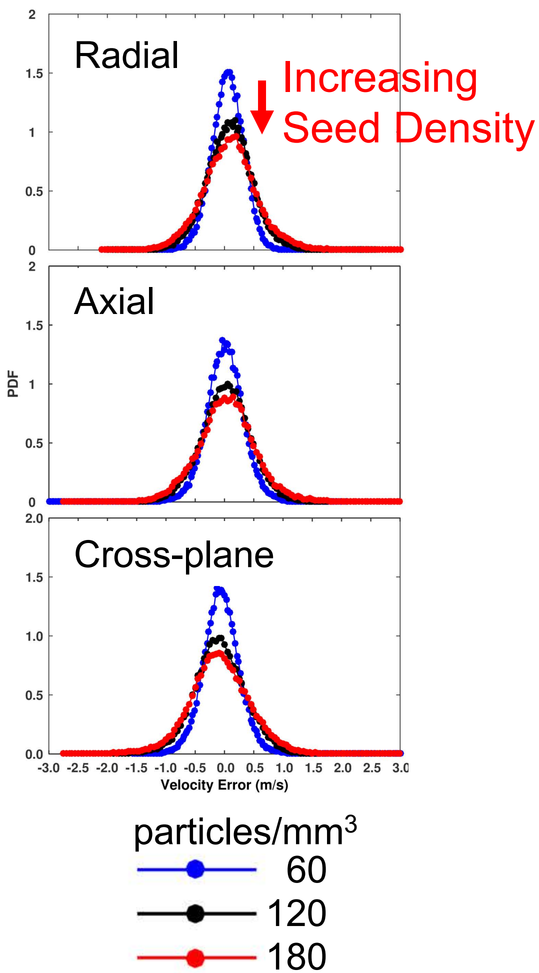
Blue regions = tomographic reconstruction

Source of Artifacts in Tomo-PIV

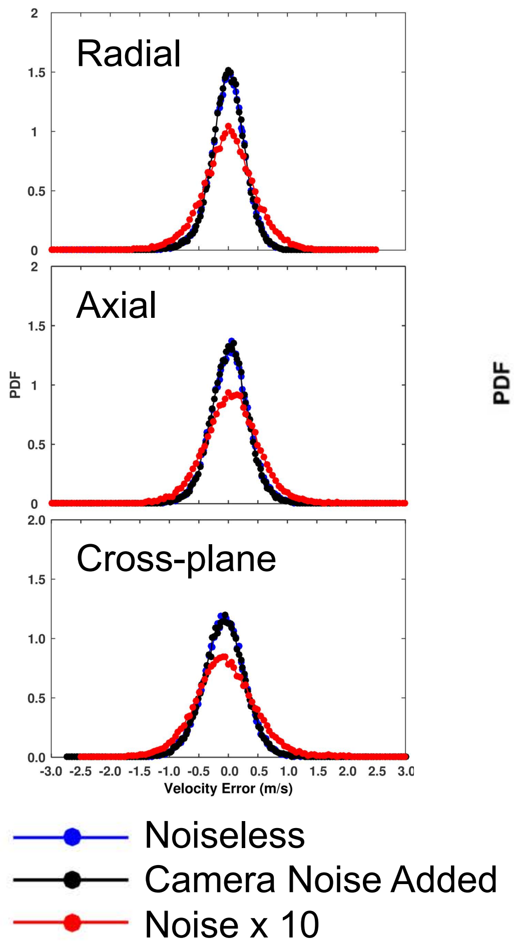


Parametric Studies of Uncertainty

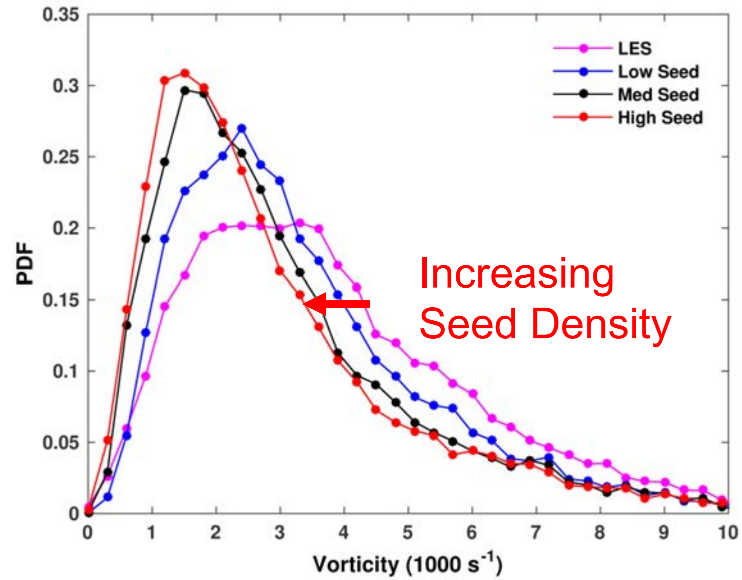
Particle Number Density



Detector Noise



Effect of Particle Number Density on Vorticity Magnitude



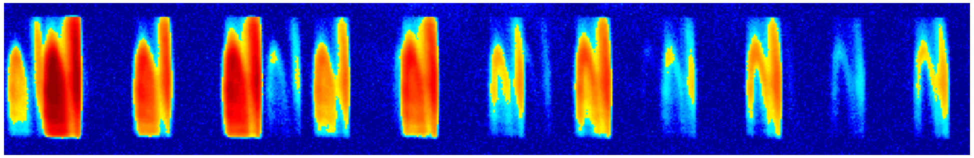
$$|\boldsymbol{\omega}| = |\nabla \times \boldsymbol{V}|$$

Summary
LES Evaluation of Tomographic PIV

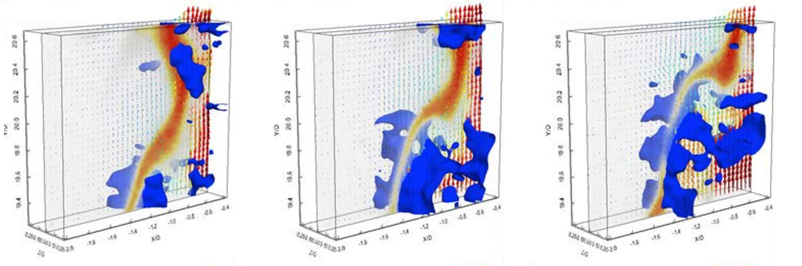
- Parametric numerical studies to assess uncertainties and improve Tomo-PIV processing in reacting flows
- Enables testing of approaches for using time-correlated data
- LES code can simulate Tomo-PIV measurements using varying resolution
- Ultimately, evaluate multi-dimensional conditional statistics in experiments and simulations to study feedback between chemical reactions and turbulence accounting for differences in spatio-temporal averaging

Outline

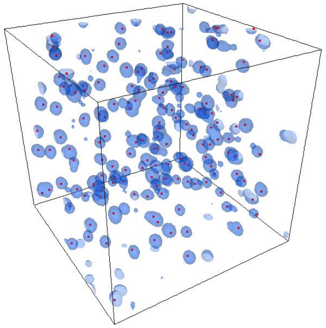
Advances in Temperature & Species Measurements



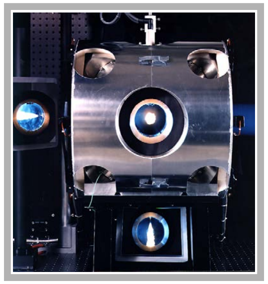
3-D Measurements of Flow Fields in Turbulent Flames

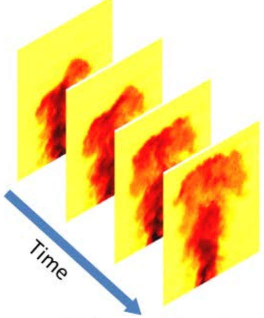


Coupling Tomo-PIV with Large Eddy Simulations



Dynamics of Transient Flows in Challenging Environments

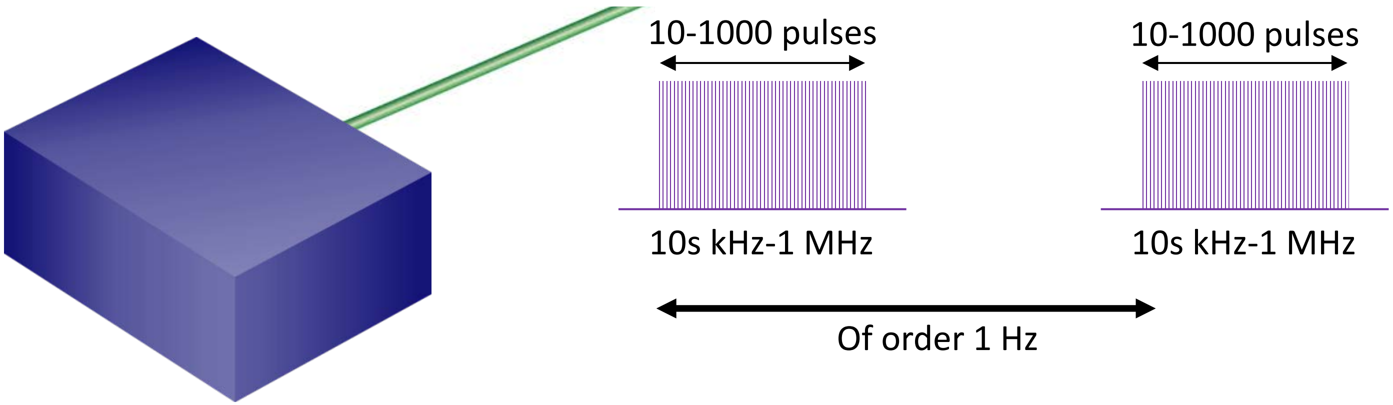


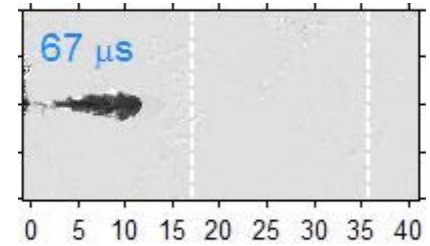


Diagnostics in Challenging Environments

- Limited optical access
- Measurements through windows and near surfaces
- High-speed flows, small length scales
- Interferences (laser-generated, background), optical density
- Beam steering
- Pressure effects on spectroscopy
- Multi-phase flows

Burst-Mode Lasers Well-Suited for Imaging High-Speed Transient Flows

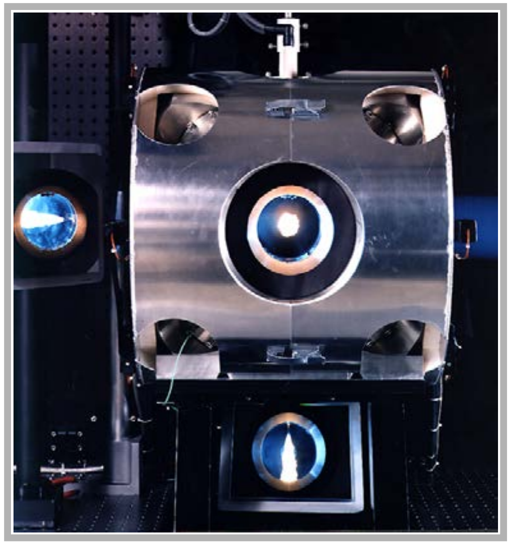




Balance pulse energy and repetition rate requirements with laser thermal load, optical damage thresholds

Diode pumping offers improved efficiency

Advances in Imaging Diagnostics Applied to High-Pressure Fuel Injection

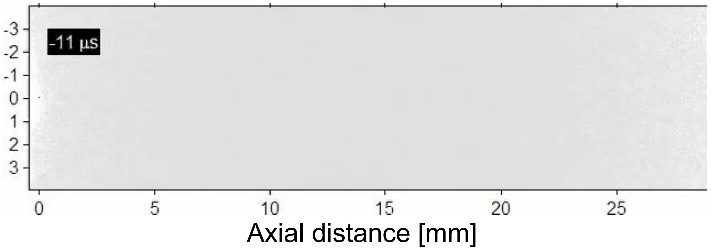


High-Pressure Fuel Injection for IC Engines

Previous Imaging Capabilities

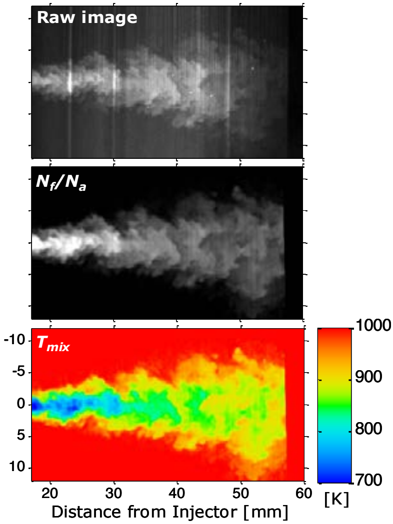
Line-of-sight Measurements

- Limited diagnostic techniques
- Difficult to interpret



Single-shot planar imaging

- Missing insight into dynamics

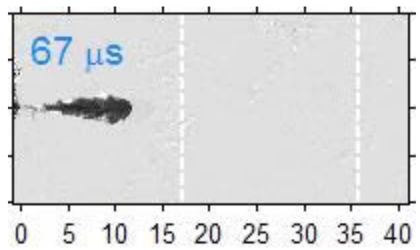


Diesel Ignition/Combustion Linked to Transient Mixing

Diesel "Spray A" conditions

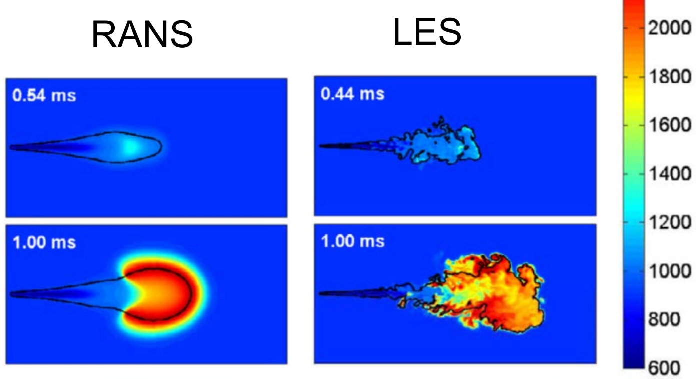
Ambient Gas	Fuel
900 K	373 K
60 bar	1500 bar
15% O_2	n-dodecane
	90 μm nozzle

150 kHz schlieren imaging



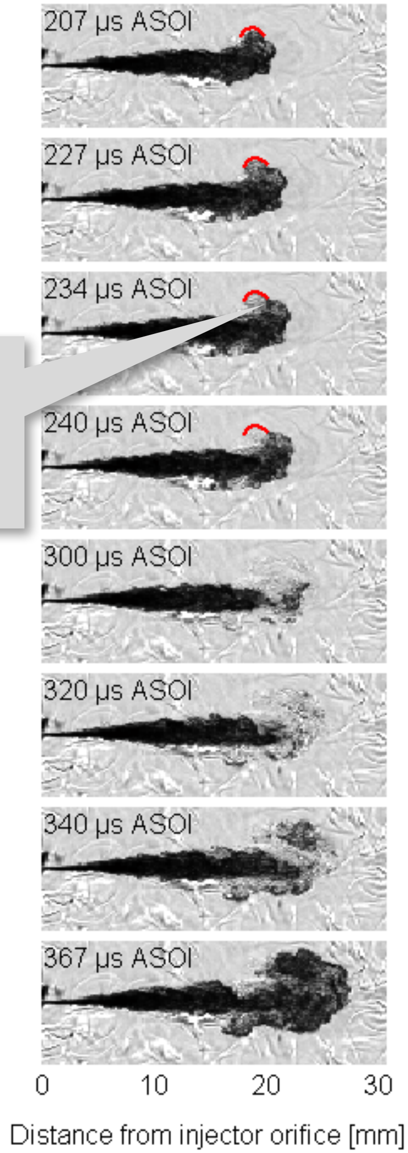
How does local mixture state evolve prior to autoignition?

- Cool flame initiates in
  - Schlieren "transpare
    scale organization
  - Cool flame temperature close to 900 K
- High-temperature ignition occurs in the "head" region
  - Low-density (2000 K) zones appear again
  - Flame "lift-off" stabilizes at approx. 17 mm
- Accurate CFD modeling of ignition is needed

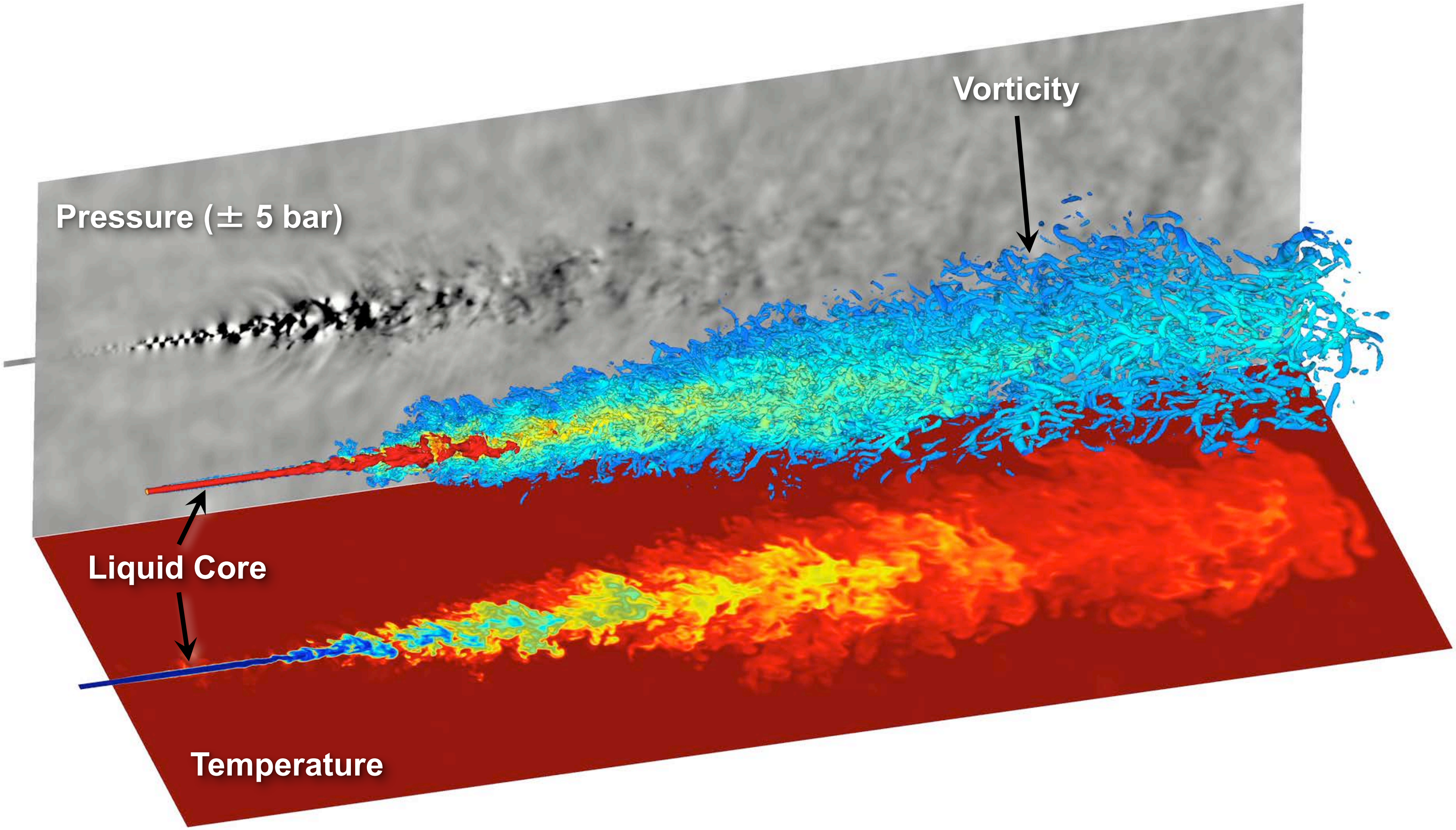


Pei et al. Combust. Flame 162:4442 (2015)

Schlieren

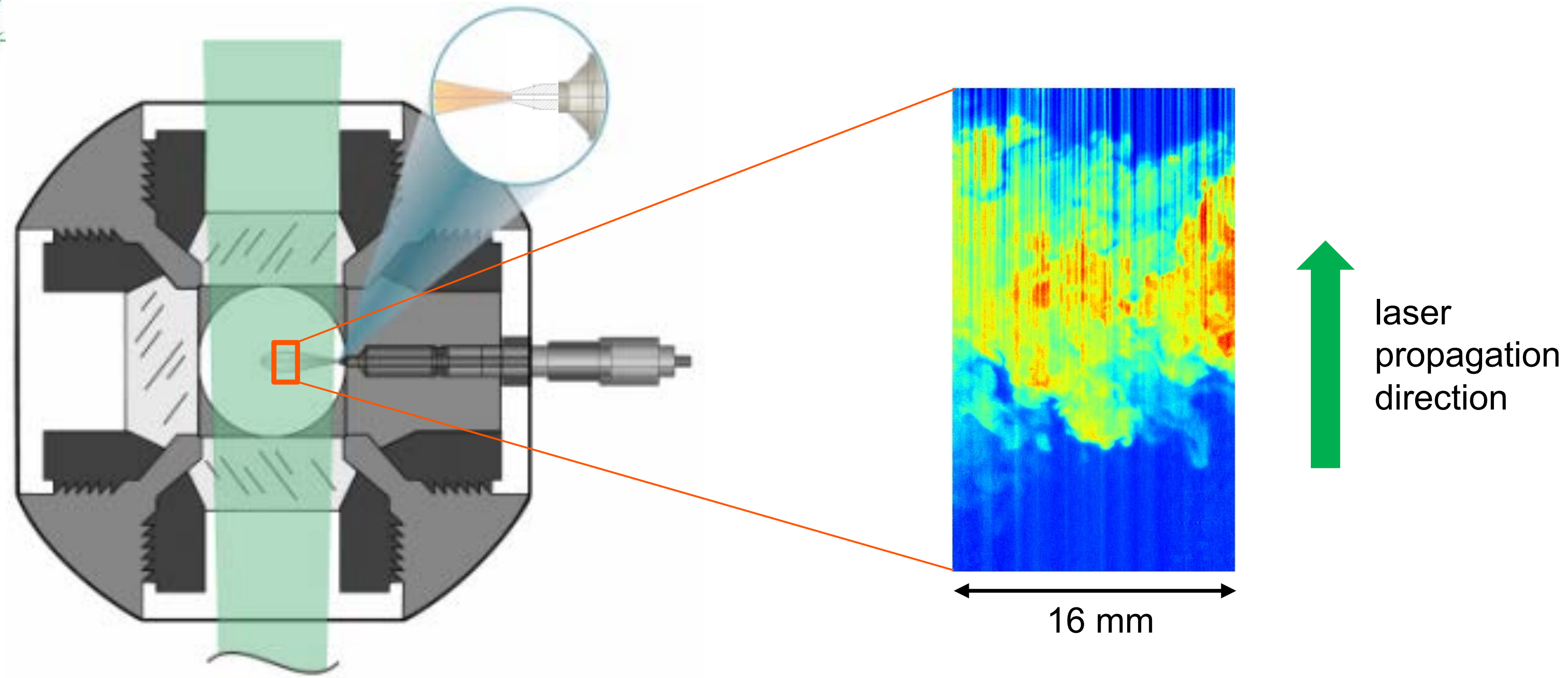


Transient Evolution of Jet Shows Detailed Structural Flow Interactions



Large Eddy Simulation by Joe Oefelein & Guilhem Lacaze

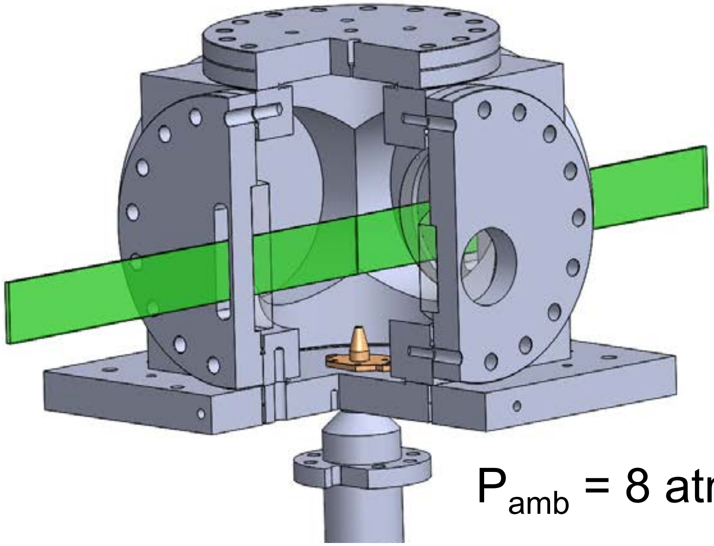
Beam Steering

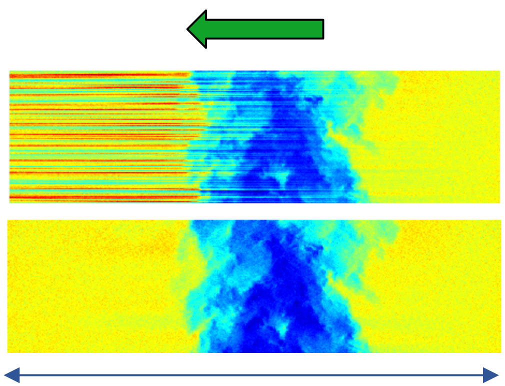


How to correct for beam steering artifacts?

- Ray-tracing algorithms have proven useful at atmospheric pressure (Kaiser, Frank, Long *Appl. Opt.* 2005).
- Challenge for ray-tracing increases with pressure.
- Investigate additional approaches

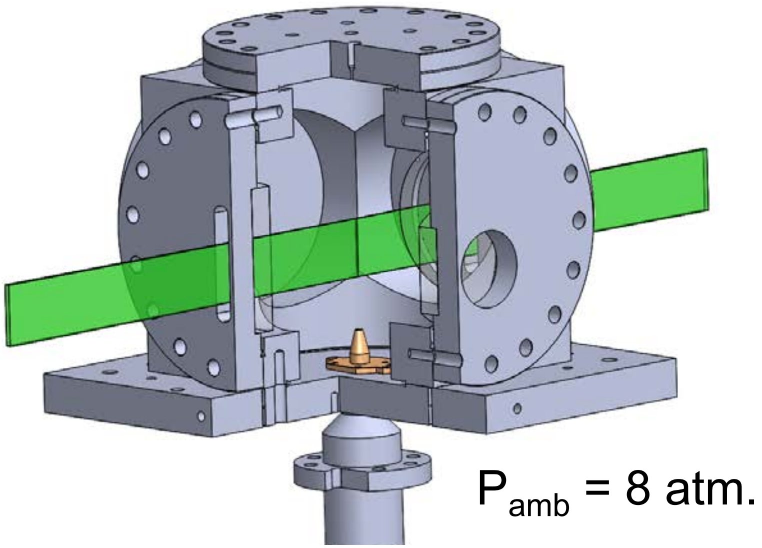
Development of Beam Steering Correction for High-Pressure Imaging

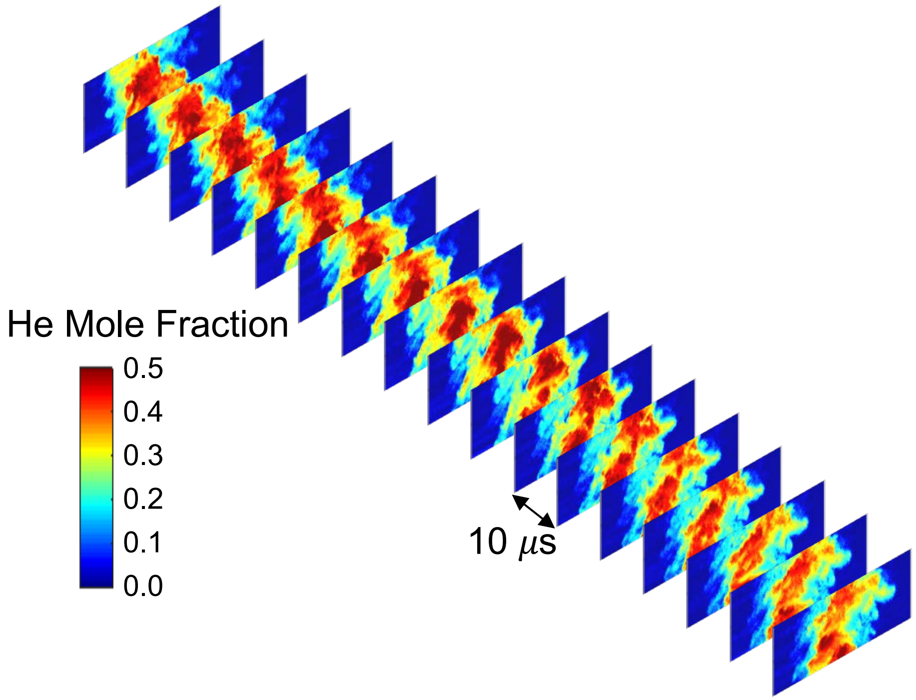




Developed wavelet-based method to correct for beam-steering effects while minimizing impact on physical structures

Rayleigh Scattering Imaging of Transient Gas Jet at Elevated Pressure



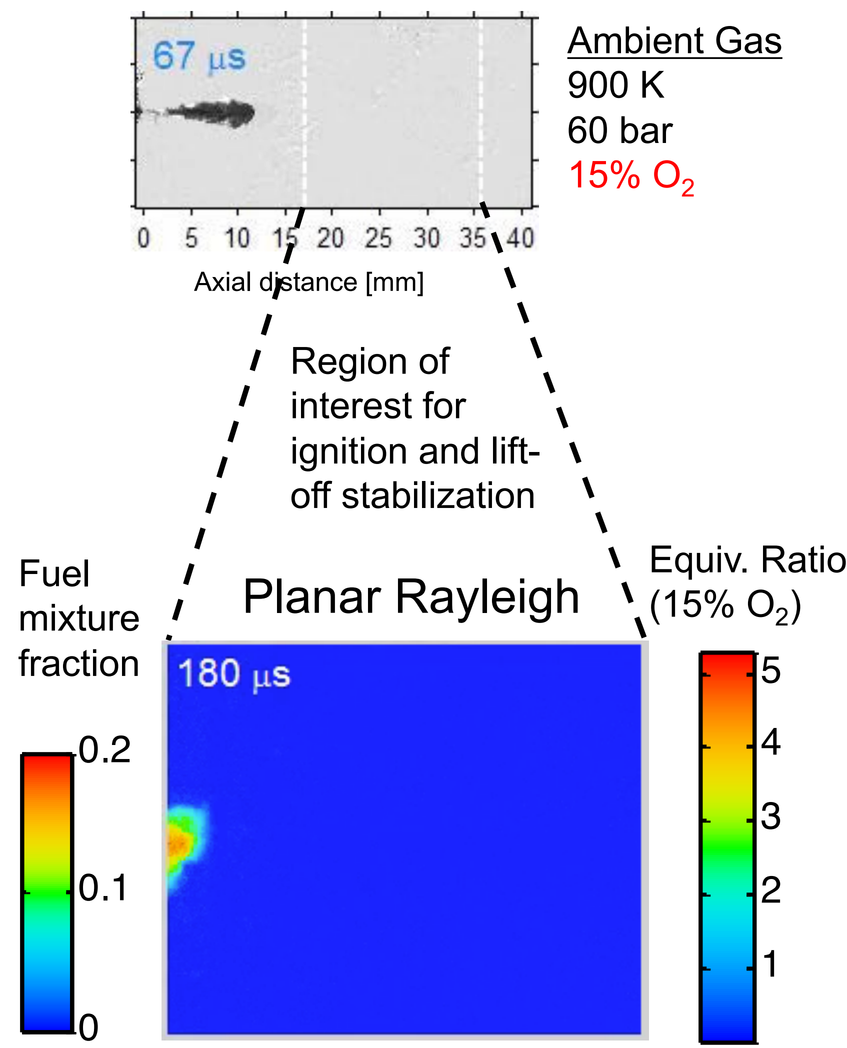


Transient injection of He into CH_4 bath gas

Transient spray mixture fraction measured in vaporized region of non-reacting injection

- Rayleigh scattering quantifies transient mixture fraction / equivalence ratio
  - Target condition Spray A has massive research effort to understand engine spray combustion (Engine Combustion Network)
- Jet mixing - large structures shed to side and re-entrained
  - Larger residence time in hot mixtures
- Target for high-fidelity LES studies
  - Verify turbulent mixing field as preliminary step towards predicting ignition/combustion

150 kHz schlieren imaging

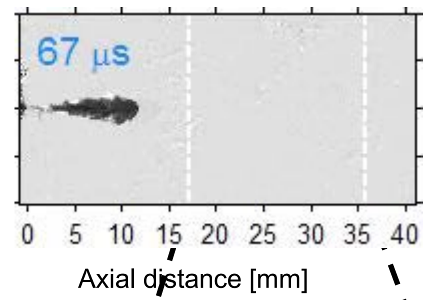


Ambient Gas
900 K
60 bar
0% O_2

Transient Temperature History Important for Ignition

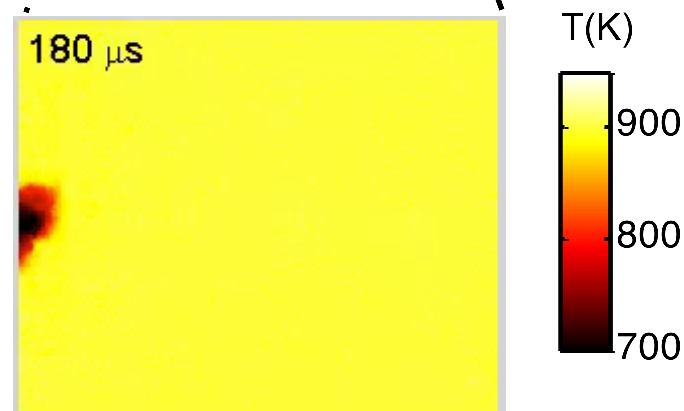
- Rayleigh scattering quantifies transient mixture fraction / equivalence ratio
  - Target condition Spray A has massive research effort to understand engine spray combustion (Engine Combustion Network)
- Jet mixing - large structures shed to side and re-entrained
  - Larger residence time in hot mixtures
- Target for high-fidelity LES studies
  - Verify turbulent mixing field as preliminary step towards predicting ignition/combustion

150 kHz schlieren imaging



Ambient Gas
900 K
60 bar
15% O_2

Region of interest for ignition and lift-off stabilization

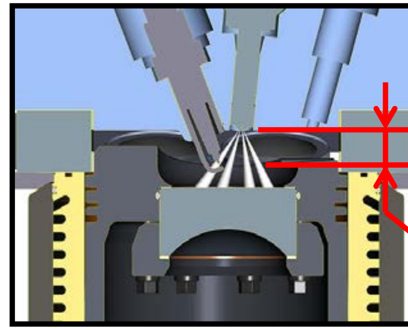


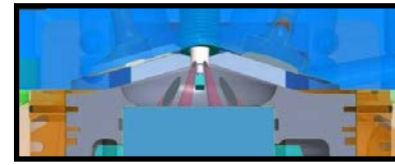
Ambient Gas
900 K
60 bar
0% O_2

Fuel spray mixing is important to efficiency

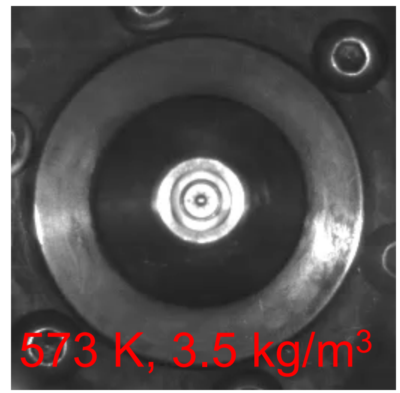
Issues in direct-injection spray

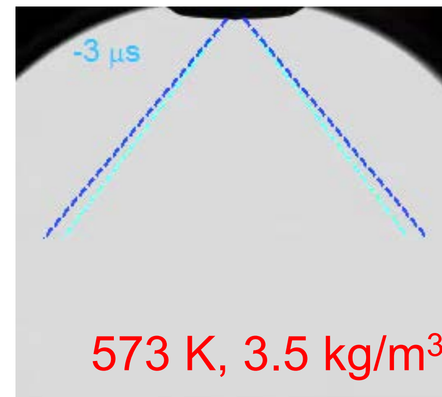
- Temperature non-uniformities
- Mixture/flow preparation near spark
- Fuel films on piston/injector, rich pockets
- Control of stratification/residence time to stage heat release



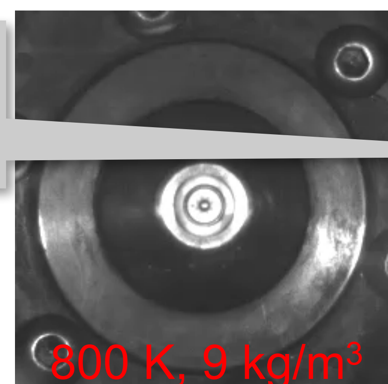


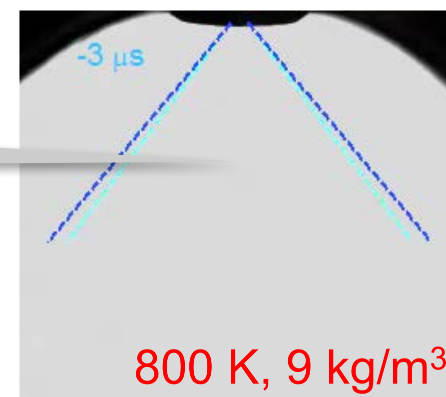
8-hole, gasoline
80° total angle
~15mm





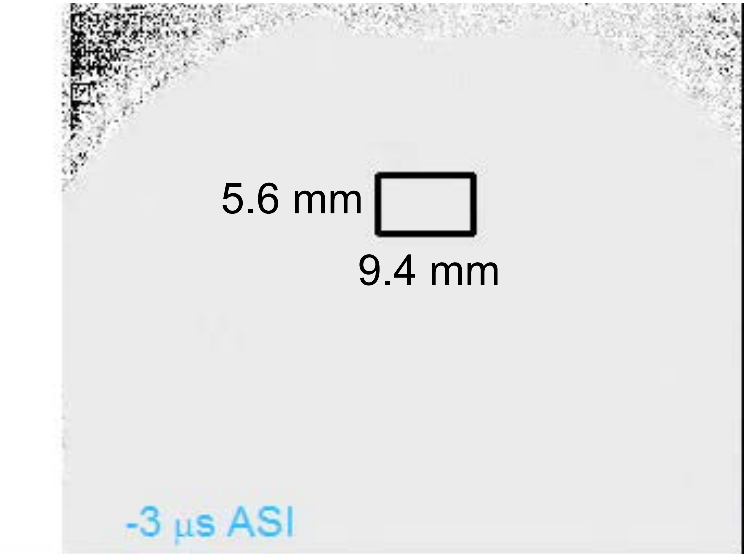
Plume collapse limits mixing of fuel with air and is not well predicted.



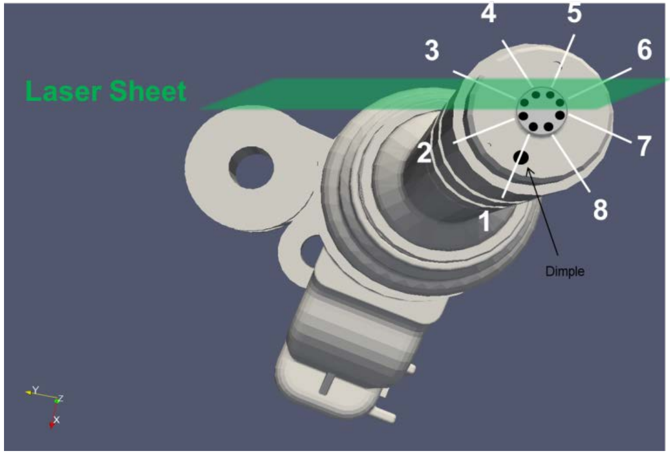


Spray "G" Target Case in ECN

Velocity Measurements in Central Region of Iso-octane Plumes Using PIV



Measurement plane between plumes to probe central region



<u>Pulse-burst laser system</u>

100 kHz pulse pairs

500 pulse pairs (5 ms burst)

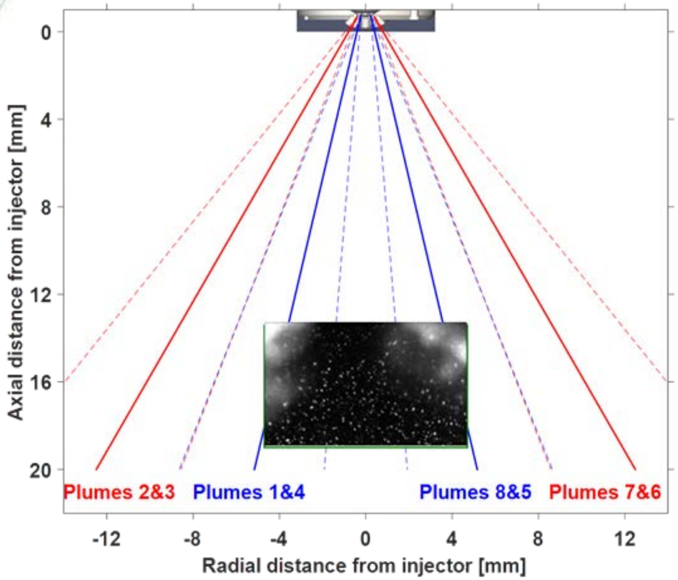
15 mJ/pulse, λ = 532 nm

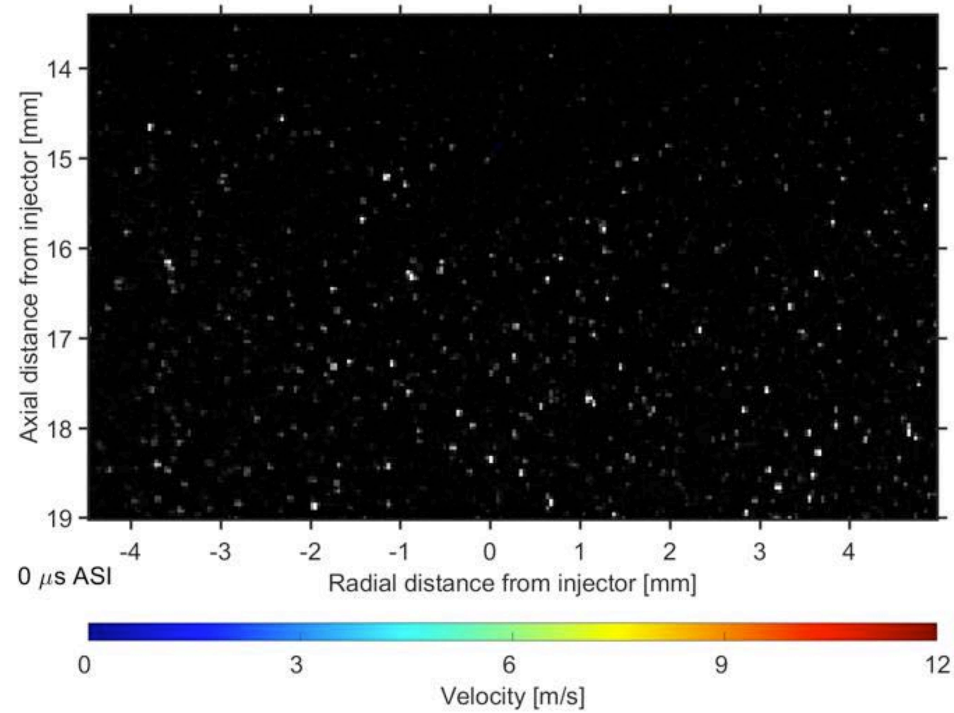
<u>Ambient Gas</u>	<u>Fuel</u>
573 K	363 K
6 bar	200 bar
3.5 kg/m^3	iso-octane
0% O_2	170 μm nozzle

Plumes remain separate during injection but then merge at the end of injection

Time Evolution of Velocity Between Plumes

15mm 573K 3.5kg/m^3

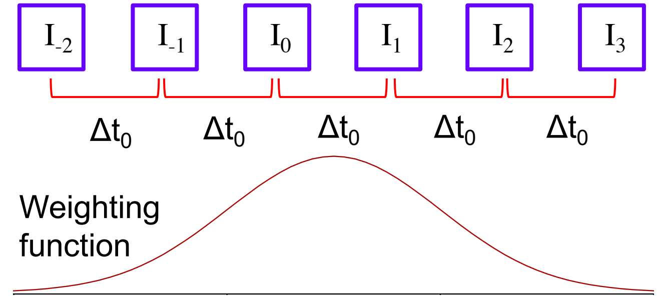




PIV improved by dynamic background subtraction

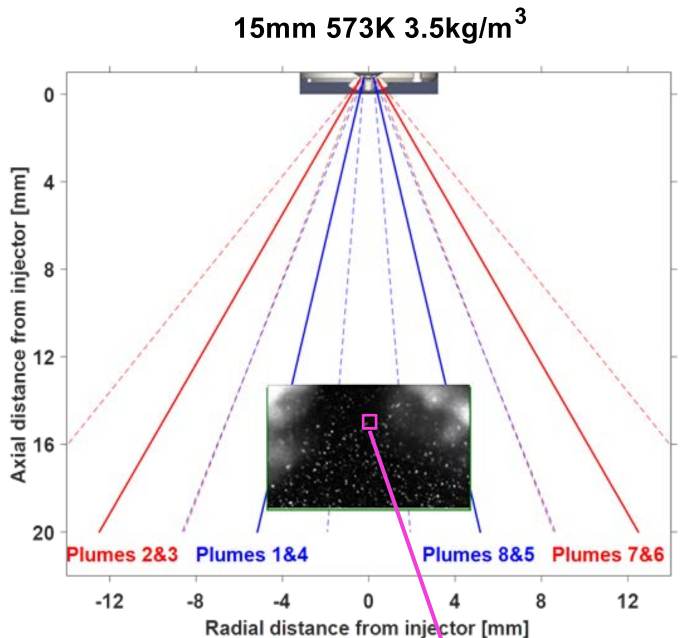
Temporal filtering schemes useful For challenging environments

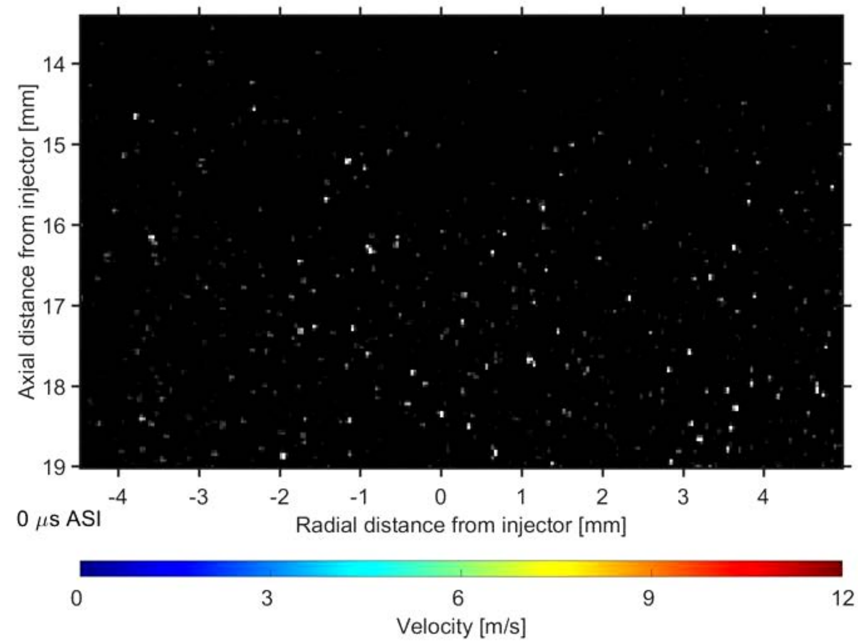
Particle displacement calculation using sliding sum of correlations

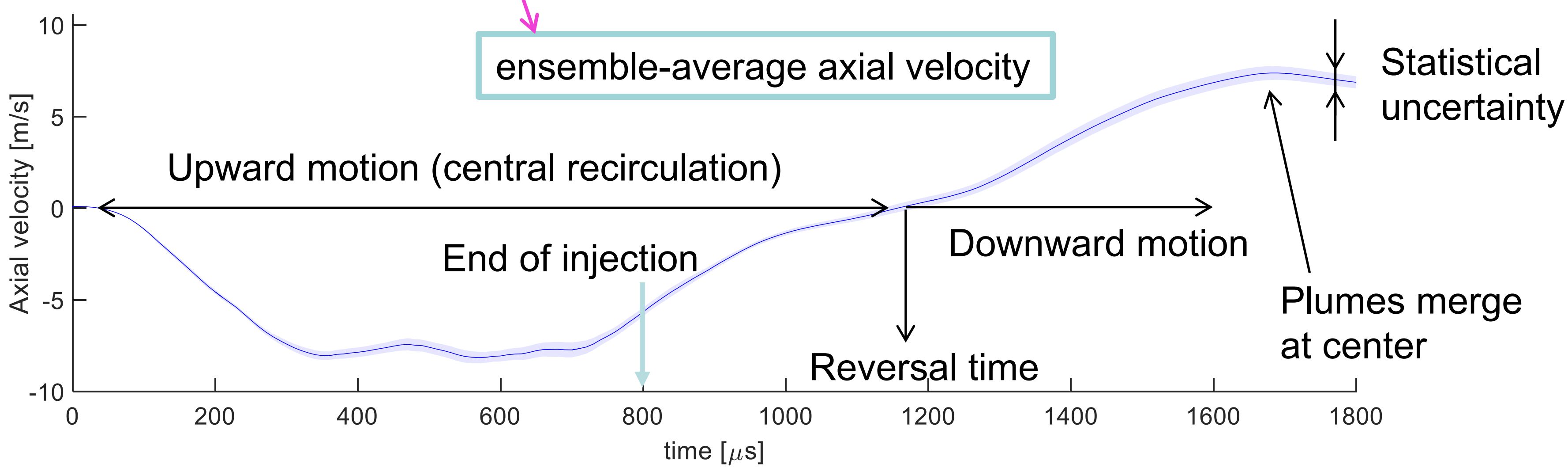


Adaptive filter schemes: Sciacchitano, Scarano, Wieneke, Exp. Fluids 53 (2012)

Time Evolution of Velocity Between Plumes







Summary
Imaging of High-Pressure Fuel Injection with Pulse-Burst Laser

- Planar imaging at 100 kHz at elevated pressures and temperatures
- Rayleigh scattering imaging of n-dodecane mixing
- Development of method for treating beam-steering
- PIV of iso-octane mixing in gasoline injector
- Captured flow reversal leading to plume collapse
- Ongoing investigation of different injection conditions and further planar imaging diagnostics

Themes in Laser Imaging Diagnostics for Understanding Turbulence-Flame Interactions

- Advances in dimensionality of diagnostics
  - Dynamics & structure of turbulence-chemistry interactions
    - velocity/species/temperature: 3D and 4D (spatio-temporal) measurements
  - Thermochemical state
    - temperature/species: single-point ➡ 1D ➡ 2D measurements
- Expanding capabilities in challenging environments
  - Approaches for treating interferences, imaging artifacts
  - Tailoring diagnostics to problem of interest
- Opportunities for coupling experiments and simulations
  - Approaches for statistical comparisons of multi-dimensional, multi-parameter datasets
  - Development and optimization of experimental and simulation methods

Acknowledgements

Sandia National Laboratories

Bruno Coriton
Adam Ruggles
Scott Bisson
Scott Skeen
Julien Manin
Brian Patterson
Erxiong Huang
Joseph Oefelein
Christopher Kliewer
Robert Barlow
Lyle Pickett
Alexis Bohlin
Anthony Ruiz
Panos Sphicas

Division of Chemical Sciences, Geosciences, and Biosciences
Office of Basic Energy Sciences, U.S. Department of Energy

Office of Vehicle Technologies, U.S. Department of Energy

Sandia Laboratory Directed Research and Development Program