SAND2017-1654PE

Probing the Structure of Turbulent Flames with Tomographic PIV and High Speed Imaging

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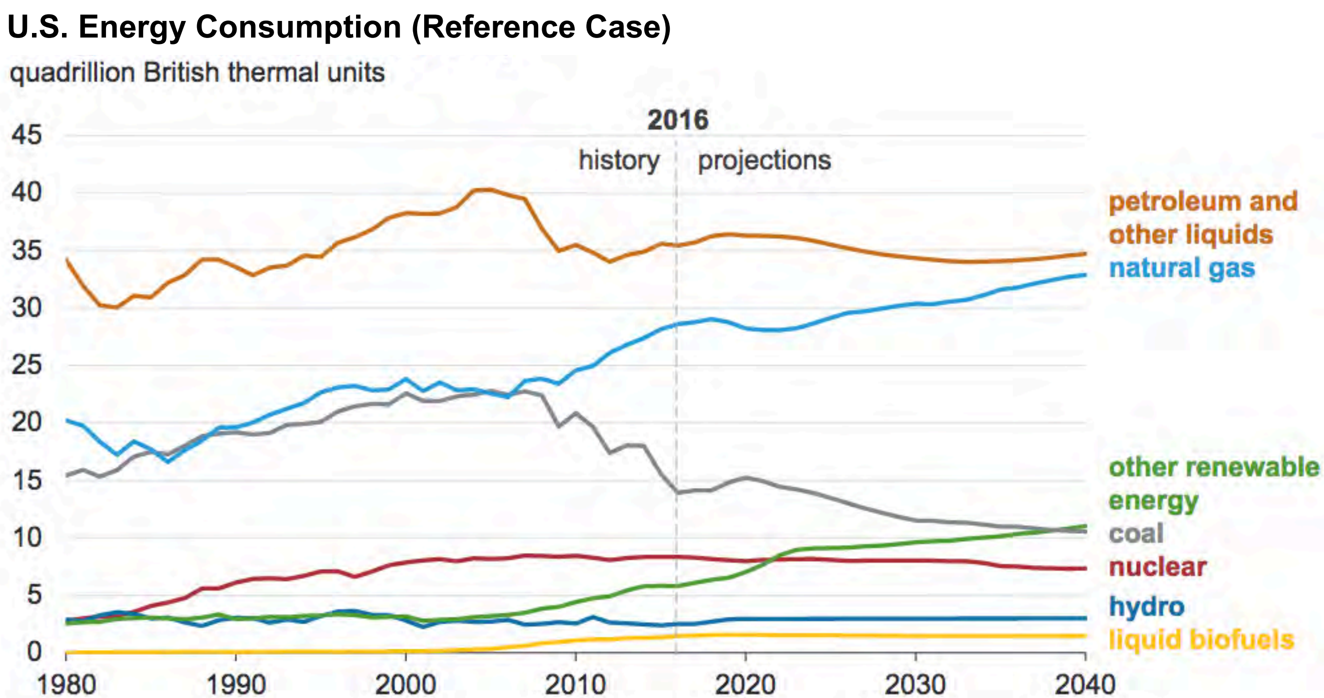
Motivation

- Improved fundamental understanding of interactions between turbulence and combustion chemistry

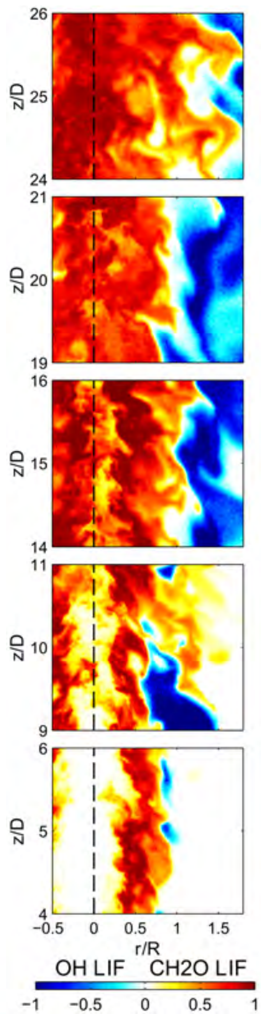
- Demand for hydrocarbon combustion for foreseeable future



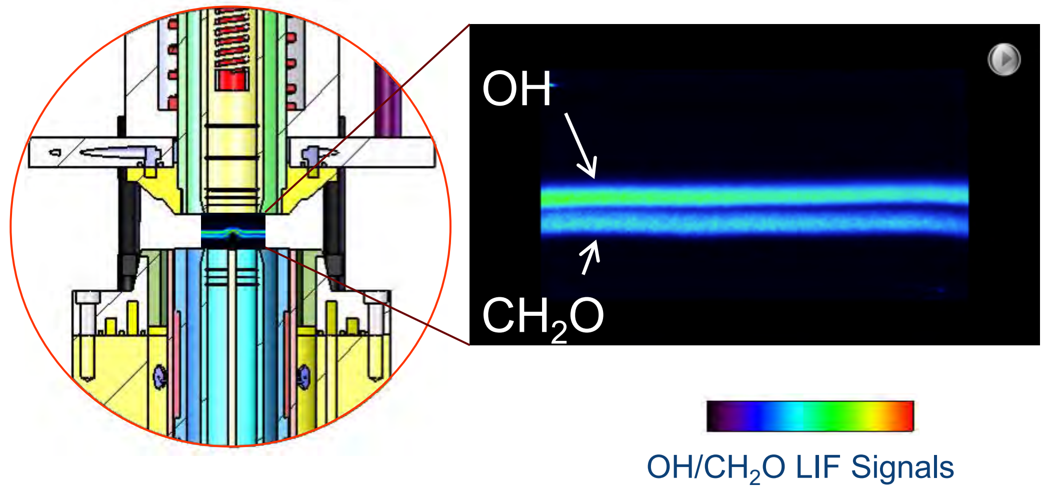
U.S. Energy Information Administration: Energy Outlook, Jan. 2017 (www.eia.gov/aeo)

Approaches to Studying Flow-Flame Interactions

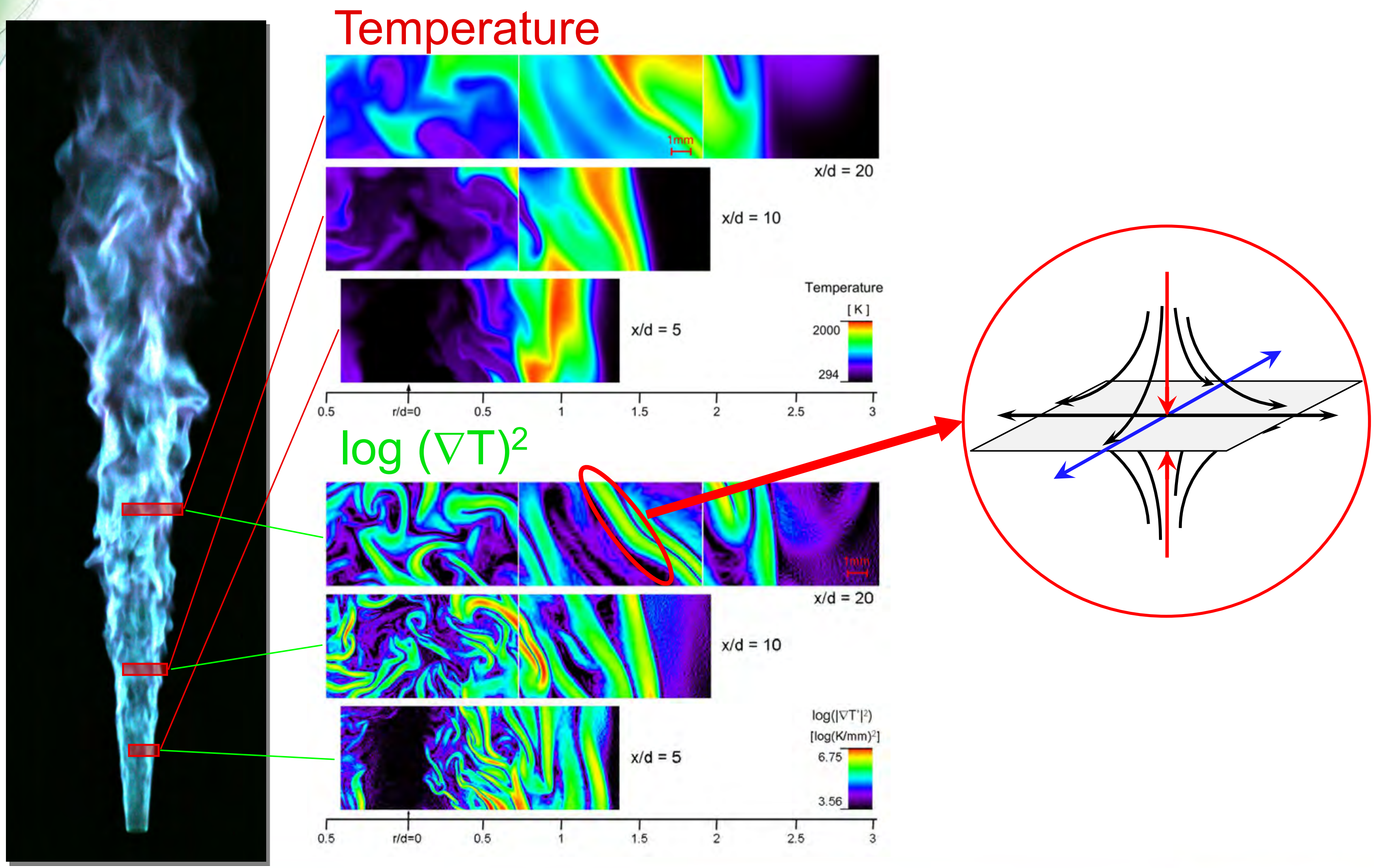
Turbulent Flows in Canonical Geometries



Isolated Repeatable Transient Flow-Flame Interactions



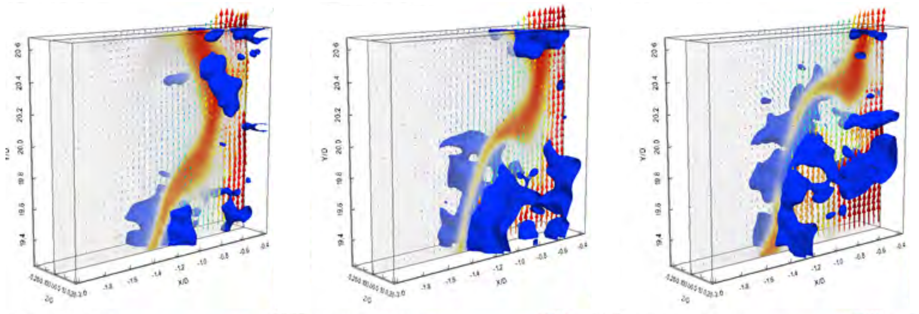
Structure of Turbulence Impacts Rates of Molecular Mixing



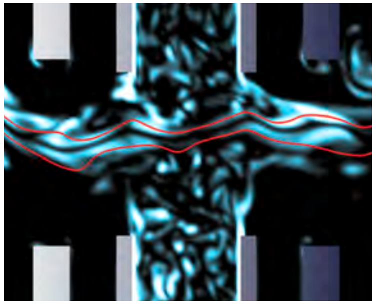
J. Frank, S. Kaiser *Exp. Fluids* 44:221 (2008)

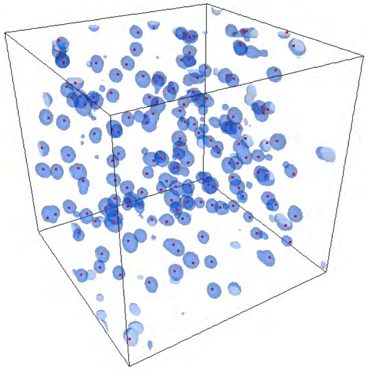
Outline

3-D Measurements of Flow Fields in Turbulent Flames

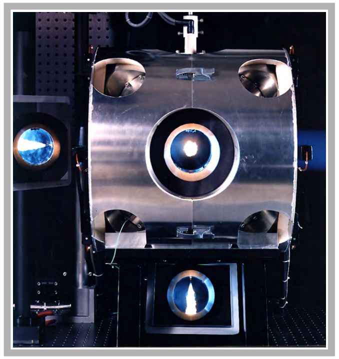


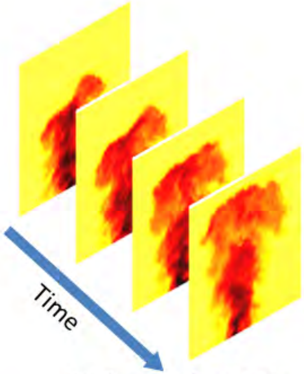
Coupling Tomo-PIV with Large Eddy Simulations





Imaging High-Pressure Fuel Injection Dynamics with Pulse-Burst Laser





Measuring Structure of Turbulence
Tomographic Particle Imaging Velocimetry (PIV)

3-Component Velocity Measurements in 3-D

$$v = u\hat{i} + v\hat{j} + w\hat{k}$$

$$\nabla v = \begin{bmatrix} \partial u/\partial x & \partial u/\partial y & \partial u/\partial z \\ \partial v/\partial x & \partial v/\partial y & \partial v/\partial z \\ \partial w/\partial x & \partial w/\partial y & \partial w/\partial z \end{bmatrix}$$

Time resolved at multi-kHz rates!

Strain Rate Measurements Enabled by Tomo-PIV

Rate of Strain Tensor

$$S = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix}$$

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

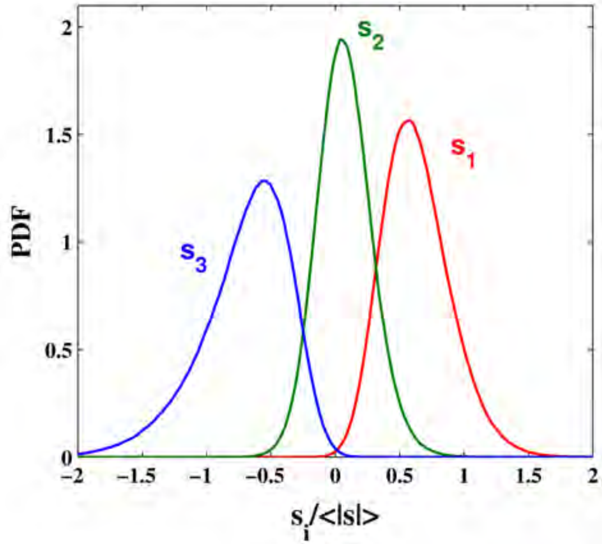
Divergence

$$\nabla \cdot u = s_1 + s_2 + s_3$$

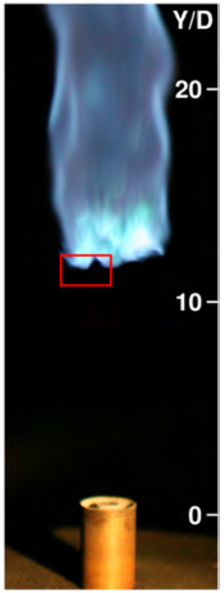
Principal Strain Rates (Eigenvalues)

$$s_1 > s_2 > s_3$$

Most Extensive (s_1), Intermediate (s_2), Most Compressive (s_3)

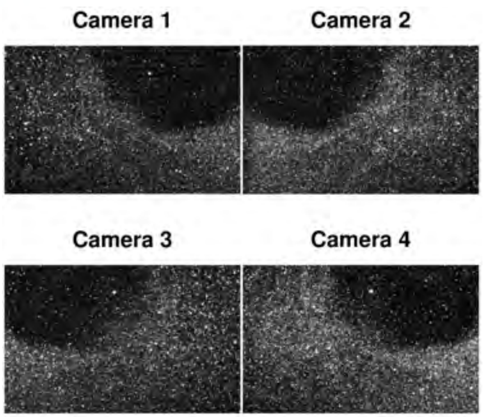


Data Acquisition and Processing
- Overview -

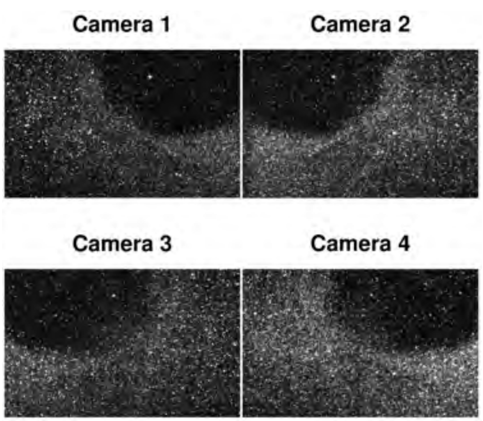


Data Acquisition

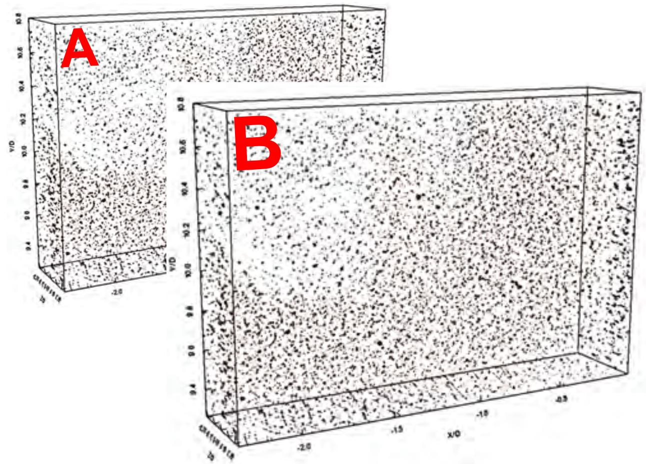
Frame A



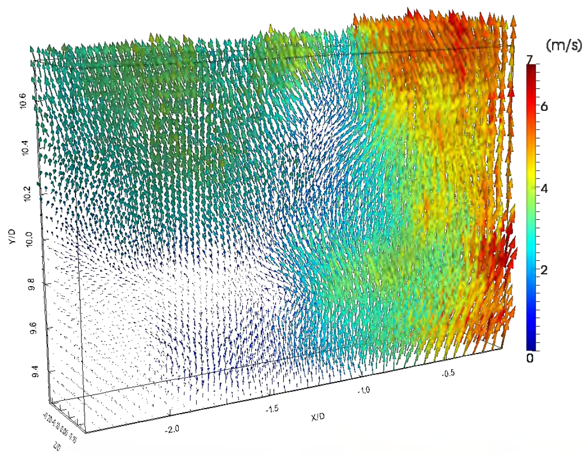
Frame B



Probe Volume Reconstruction

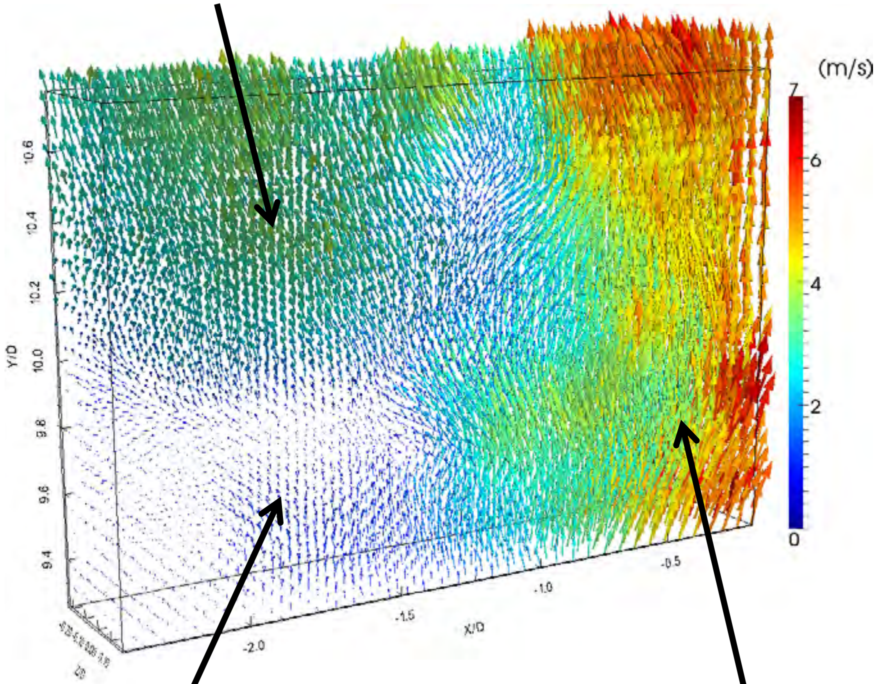


Volume Cross-Correlation



Data Processing
- Volume Cross-Correlation -

Flame products



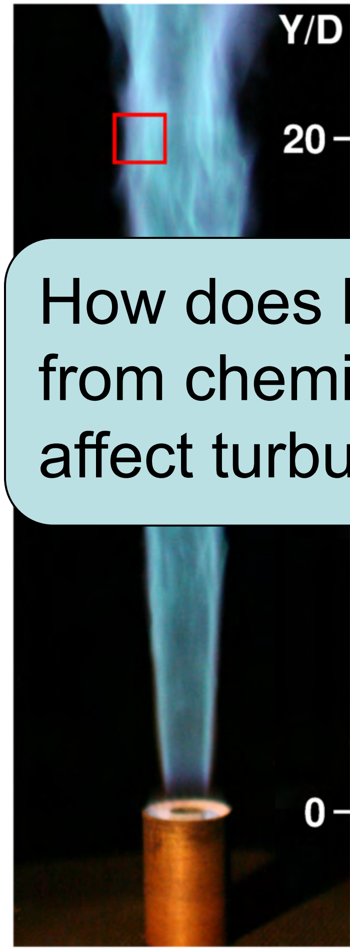
Coflow stream

Jet flow

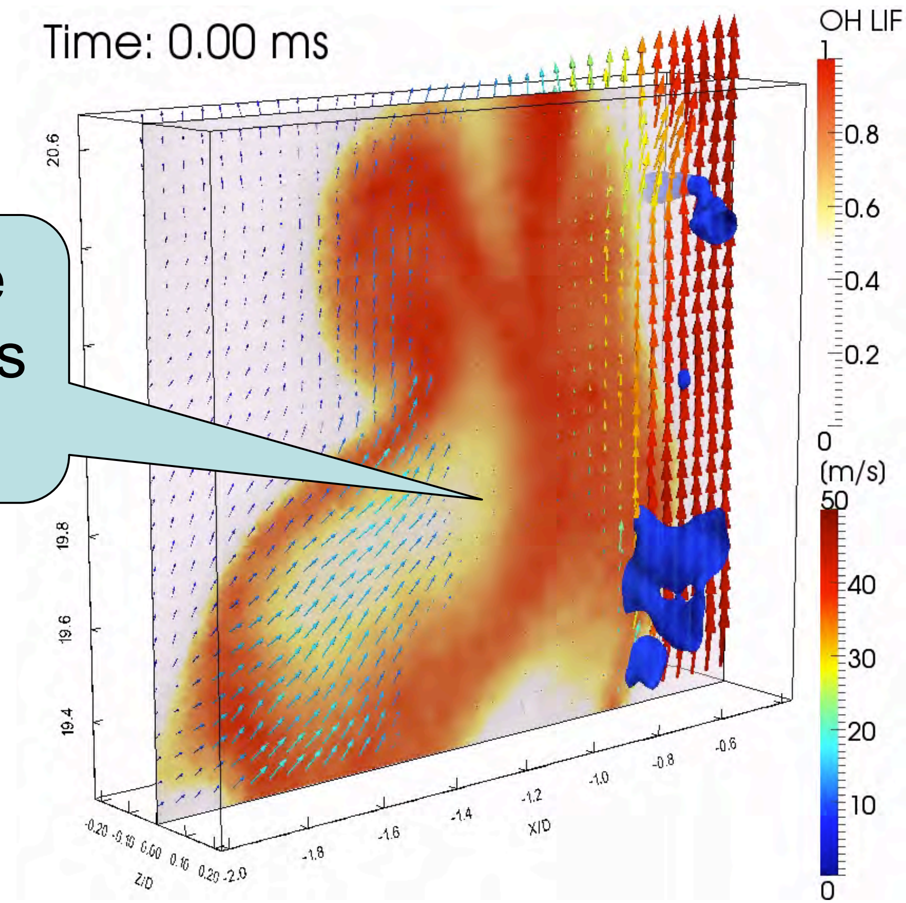
1 out of 64 vectors plotted

- Multi-pass cross-correlation analysis
- Final interrogation volume size:
  413 x 413 x 413μm^3
  24 x 24 x 24 vx
  with 75% overlap

Effects of Intermittent Strain on OH in a Turbulent Partially-Premixed Jet Flame



How does heat release from chemical reactions affect turbulence?



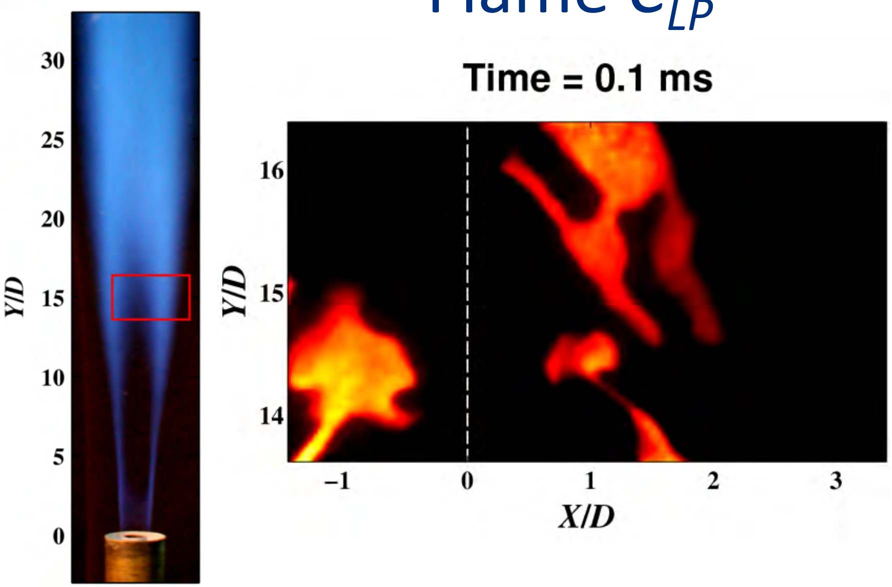
10 kHZ PIV + OH LIF

Blue isosurfaces: Γ^{3D} = -15,000 s^{-1}

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

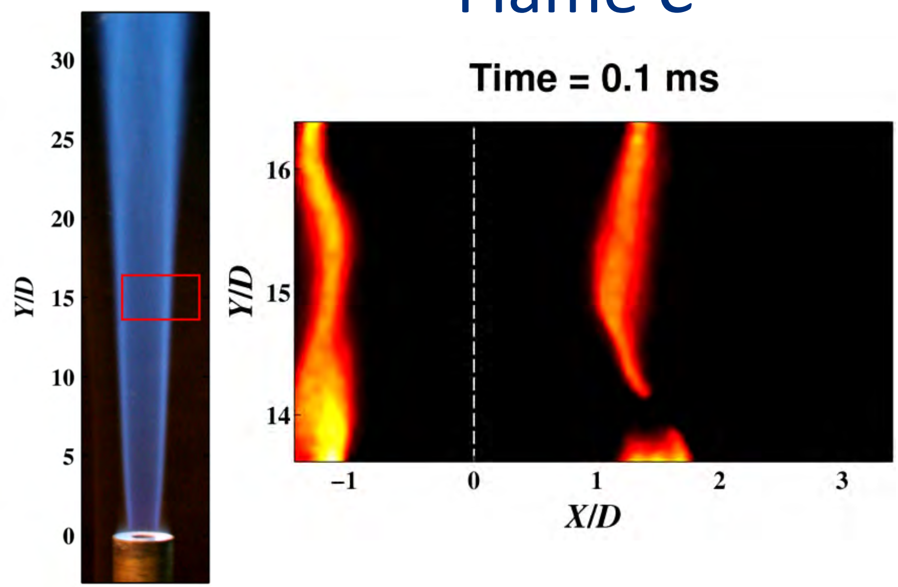
Partially Premixed CH_4/Air Jet Flames with Different Amounts of Extinction
10 kHz OH LIF Imaging

Flame C_{LP}



High probability of localized extinction and intermittent blowoff

Flame C



Flame is stable with rare extinction

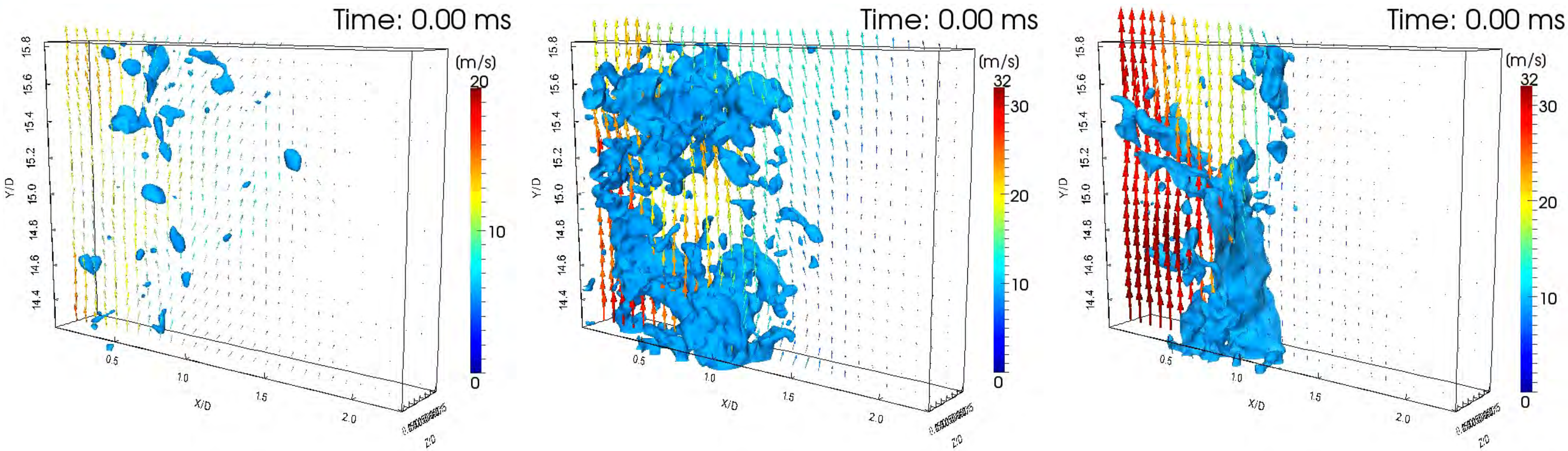
Summary of flow conditions.

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

Effects of Heat Release on Strain Rate

Increasing Heat Release

Air* Jet** | **Flame C_{LP}** | **Flame *C



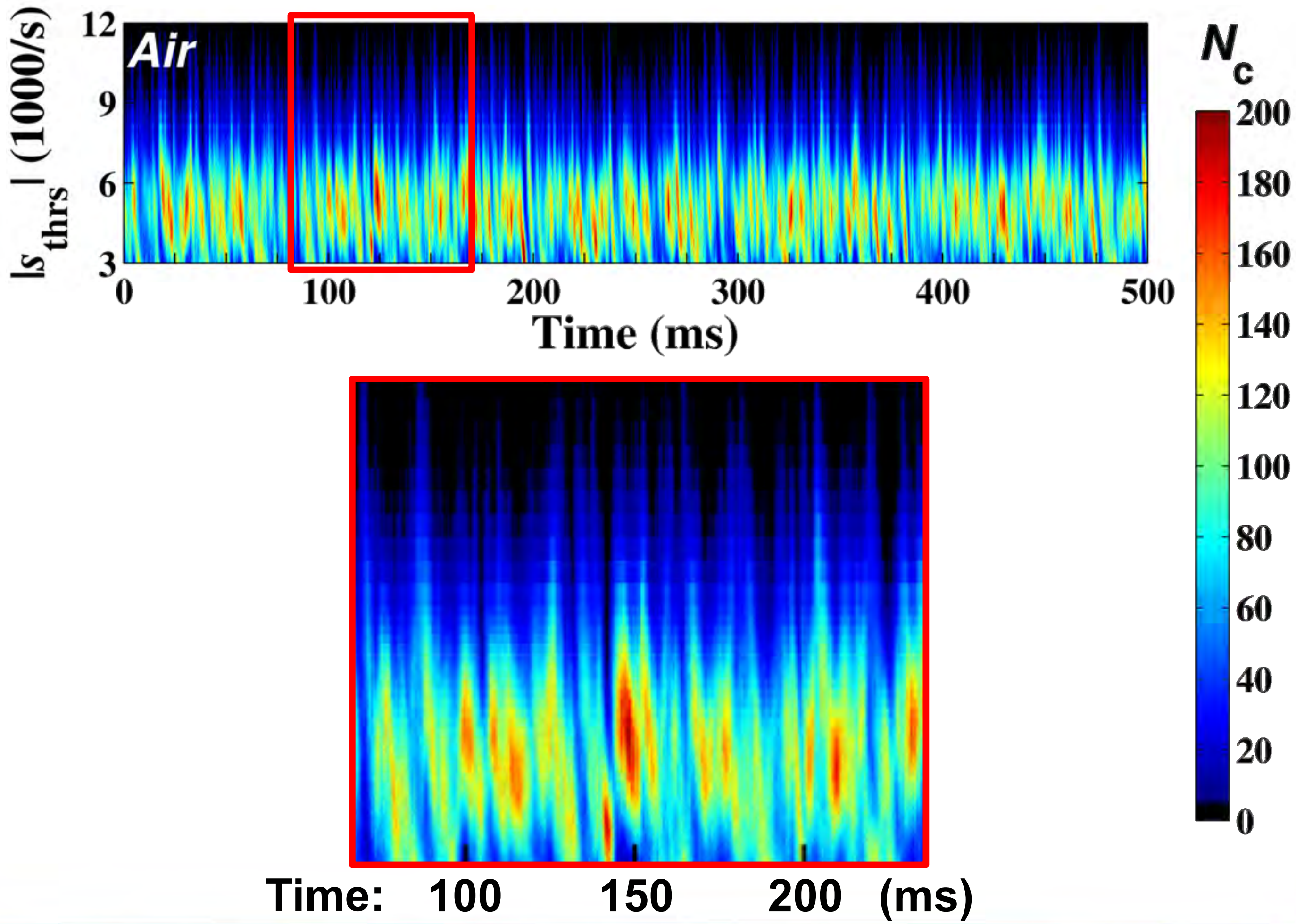
Isosurfaces for $|s_{thrs}|$ = 7,000 s^{-1}

Probe volume
16.5 mm x 12.3 mm x 2.5 mm

- Bursts of clusters
- Small fragmented structures in the core of the *Air* jet
- Large elongated structures in the fames
- Localized extinction in flame C_{LP} - features of the *Air* jet and Flame *C*

Time History of Strain Rate in Non-reacting Flow

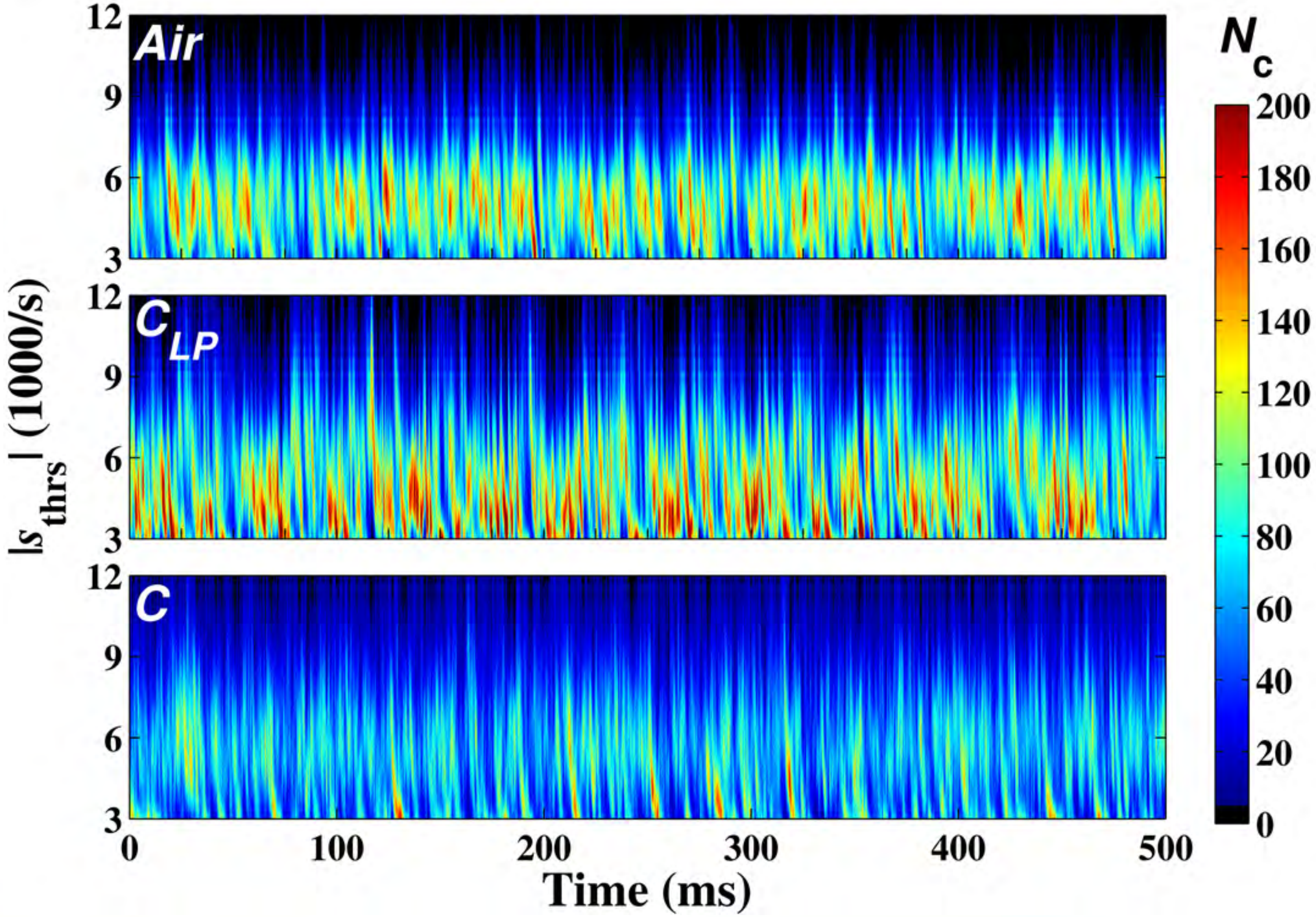
Intermittent appearances of high strain rate clusters



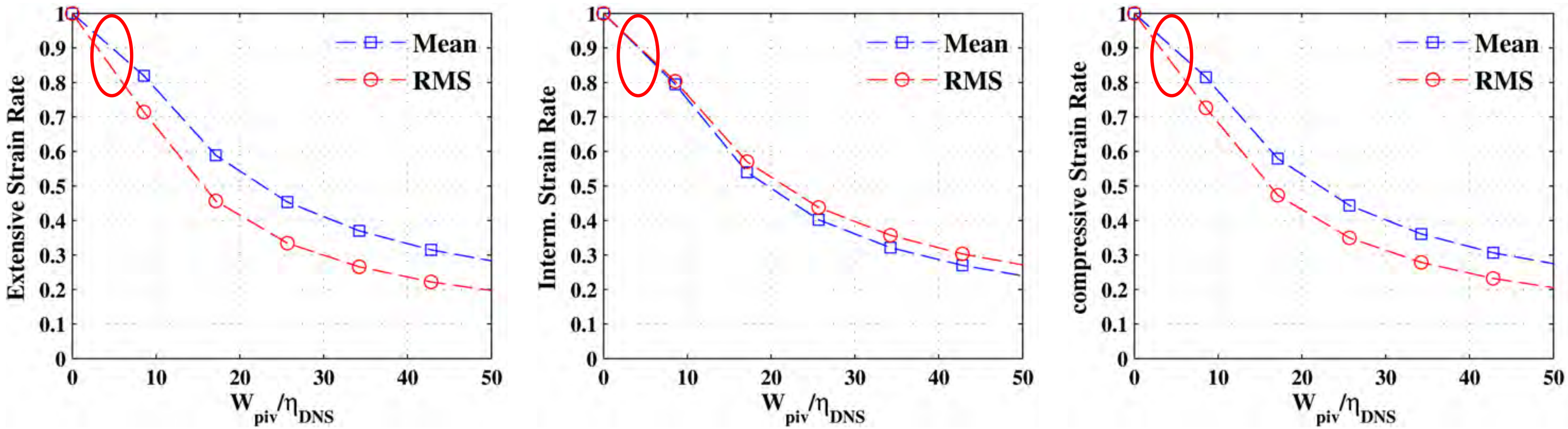
B. Coriton, J. Frank, *Proc. Combust. Inst.* 535:1243 (2015)

Effects of Chemical Reactions on Time History

Increasing Heat Release



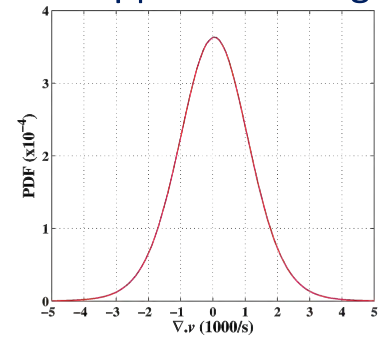
Effects of PIV Interrogation Window Size on Measured Strain Rate



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

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

Measurement Uncertainty

Sources of errors *(estimated 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 $u'\left(\frac{\lambda_m}{2\delta}\right)^{1/3}$ ~ 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}

Strain Rate - Flame Front Alignment in Premixed Flames

Transport Equation for Scalar Dissipation ($N_c = D|\nabla c|^2$)

(Swaminathan & Bray, Combust. Flame 2005)

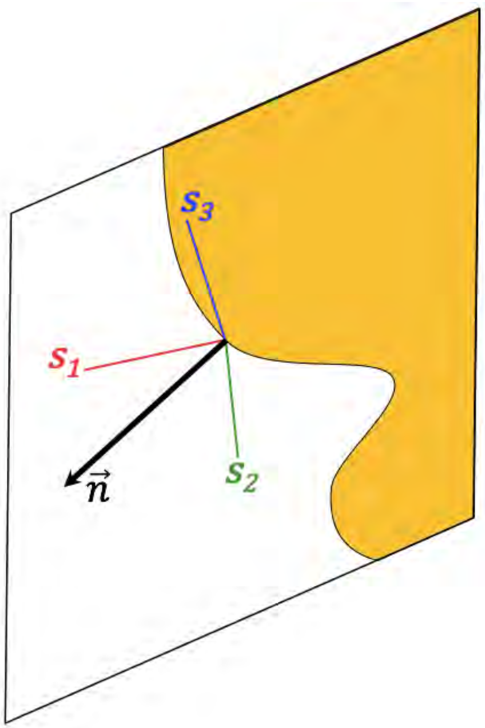
$$\rho \frac{DN_c}{Dt} = \frac{\partial}{\partial x_j}\left(\rho D \frac{\partial N_c}{\partial x_j}\right) - 2\rho D^2 \left[\frac{\partial}{\partial x_j}\left(\frac{\partial c}{\partial x_i}\right)\right]^2 + 2\rho N_c\left[\left(\delta_{ij} - n_i n_j\right) s_{ij}\right] + 2D \frac{\partial c}{\partial x_i}\frac{\partial \dot{\omega}}{\partial x_i}$$

Diffusive Flux

Dissipation of Scalar Gradient

Dilatation + Turbulence-Scalar Interaction

Production by Chemical Reaction



Flame Normal: $\boldsymbol{n} = -\frac{\nabla c}{|\nabla c|} \quad n_i = \boldsymbol{n} \cdot \hat{\boldsymbol{\imath}}$

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Diffusive Flux

Dissipation ... Sc... adient

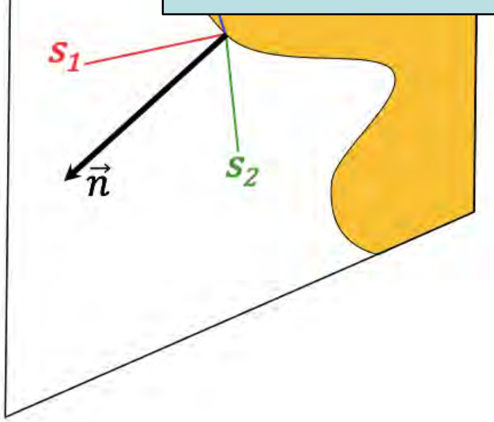
Dilatation + Turbulence-Scalar Interaction

Production by Chemical Reaction

Flame Tangential Strain

$$S_t = \left[\,(\delta_{ij} - n_i n_j)s_{ij}\right]$$

$$S_t = \Delta - S_n$$



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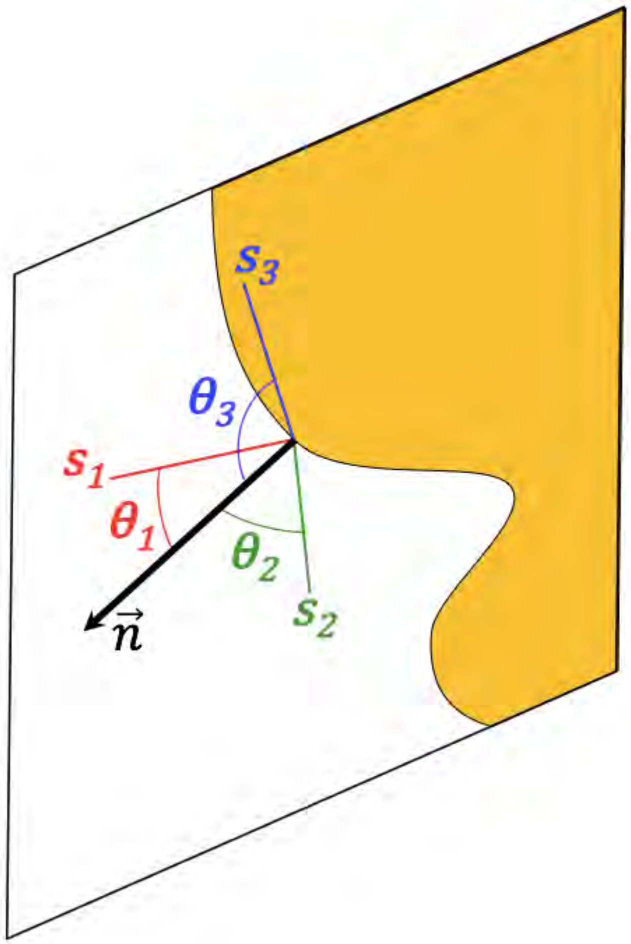
Strain Rate - Flame Front Alignment in Premixed Flames



Projection of strain along flame normal direction

$$S_n = s_1 cos^2(\theta_1) + s_2 cos^2(\theta_2) + s_3 cos^2(\theta_3)$$

Divergence = Normal Strain + Tangential Strain

$$\Delta = S_n + S_t$$

Flow Conditions for Strain Rate Alignment Measurements

Turbulent Non-reacting Flow

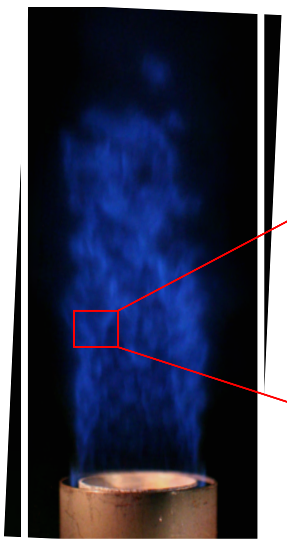
$u'(m/s)$	u'/U	$l'(mm)$	$\eta(mm)$	Re_t	$\langle\|s\|\rangle(1/s)$
0.62	8.2%	5.0	0.08	250	535

Turbulent Premixed Flames

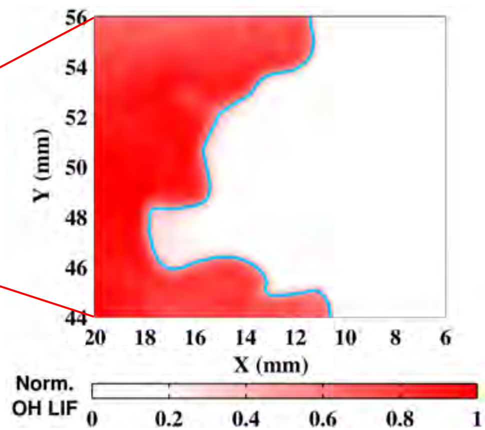
φ	τ	$S_L(m/s)$	u'/S_L	Da_t
0.65	4.8	0.15	4.1	1.7
0.80	5.8	0.24	2.6	3.0
1.00	6.5	0.34	1.8	5.1

$$\tau = \frac{T_B - T_U}{T_U}$$

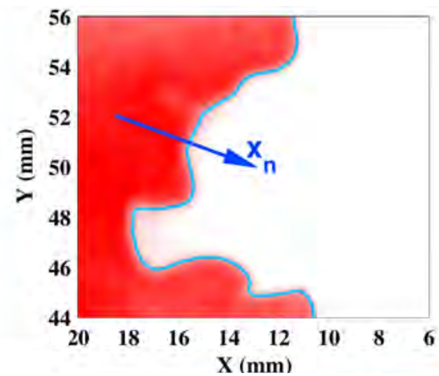
Flame Front and Strain Rate Analysis



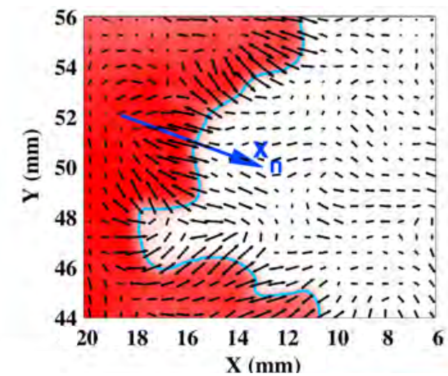
Flame front contour



Flame front normal



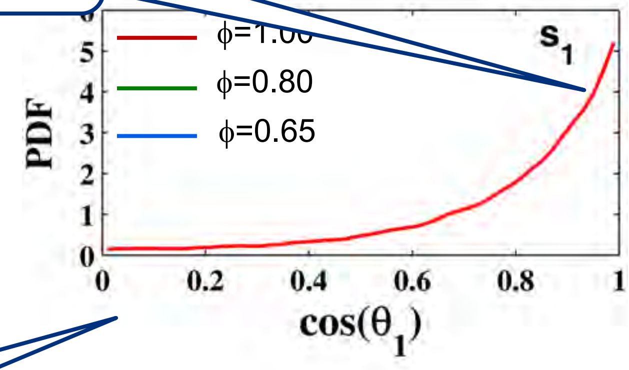
Strain rate eigenvectors

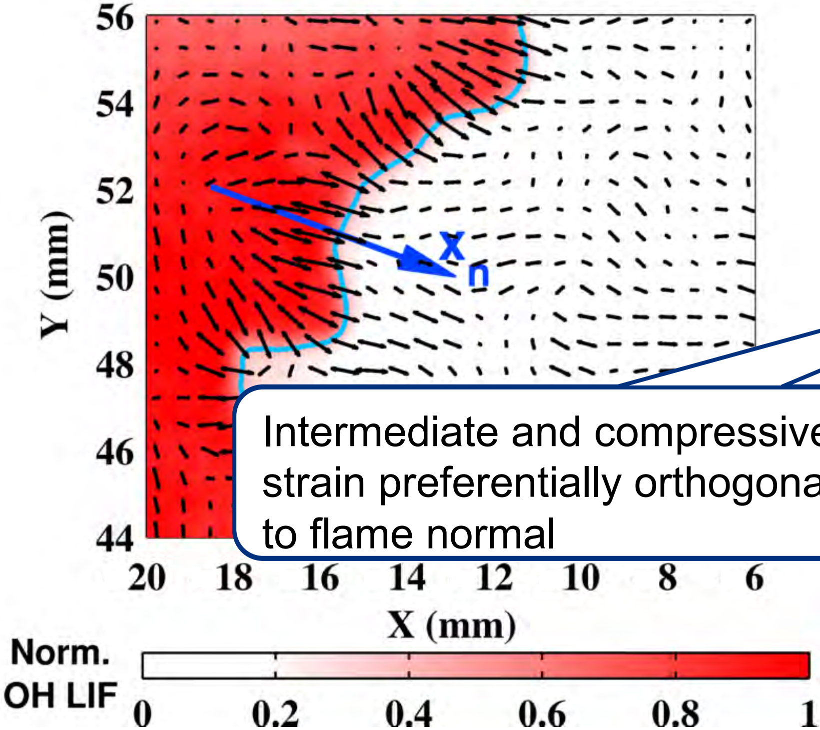


Strain-rate statistics analyzed from 5,000 single-shot TPIV measurements

Orientation of Strain Rate Eigenvectors Relative to Flame-Front Normal Direction

Extensive strain preferentially parallel to flame normal

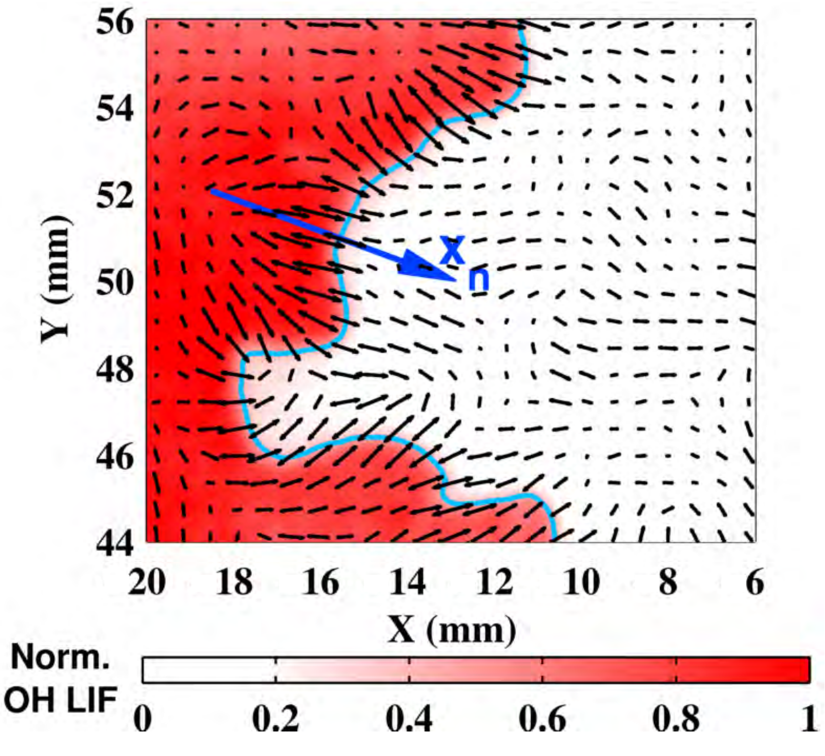


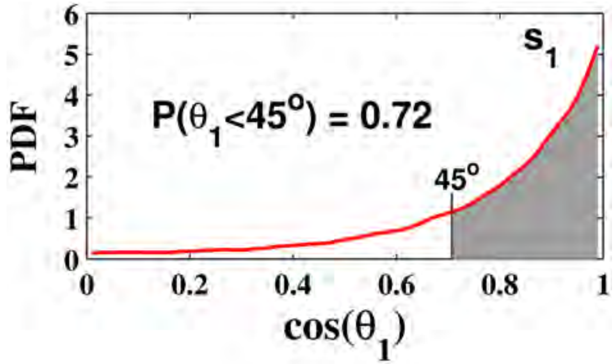


Intermediate and compressive strain preferentially orthogonal to flame normal

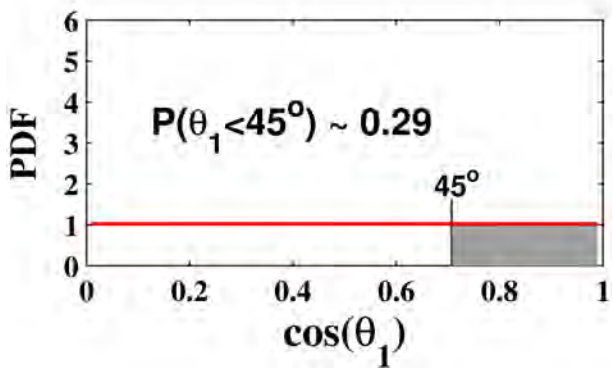
PDFs evaluated along flame front contour

Orientation of Strain Rate Eigenvectors Relative to Flame-Front Normal Direction

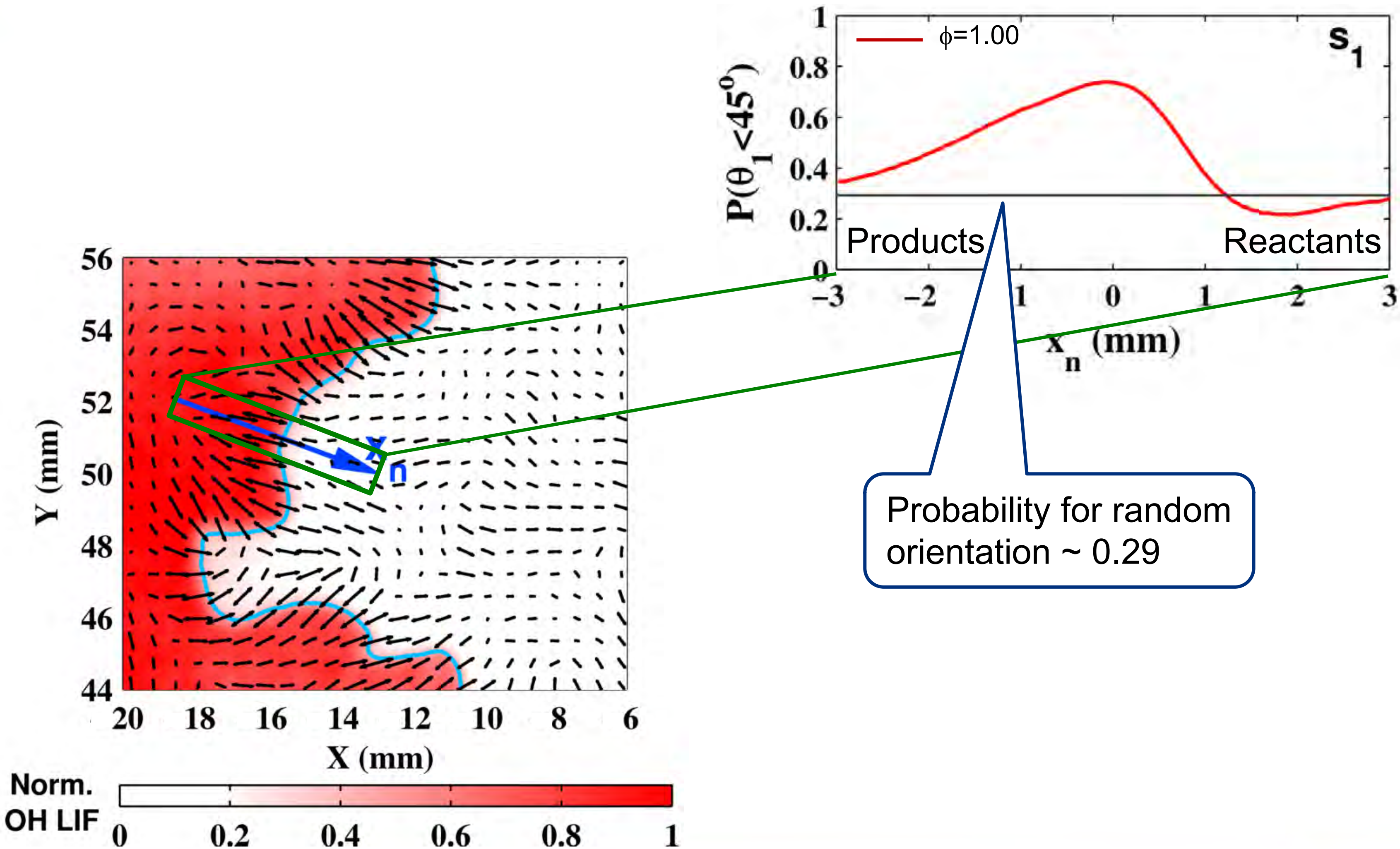




Random Orientation



Probability of Extensive Strain Rate Orientation Conditioned on Local Flame Normal Coordinate



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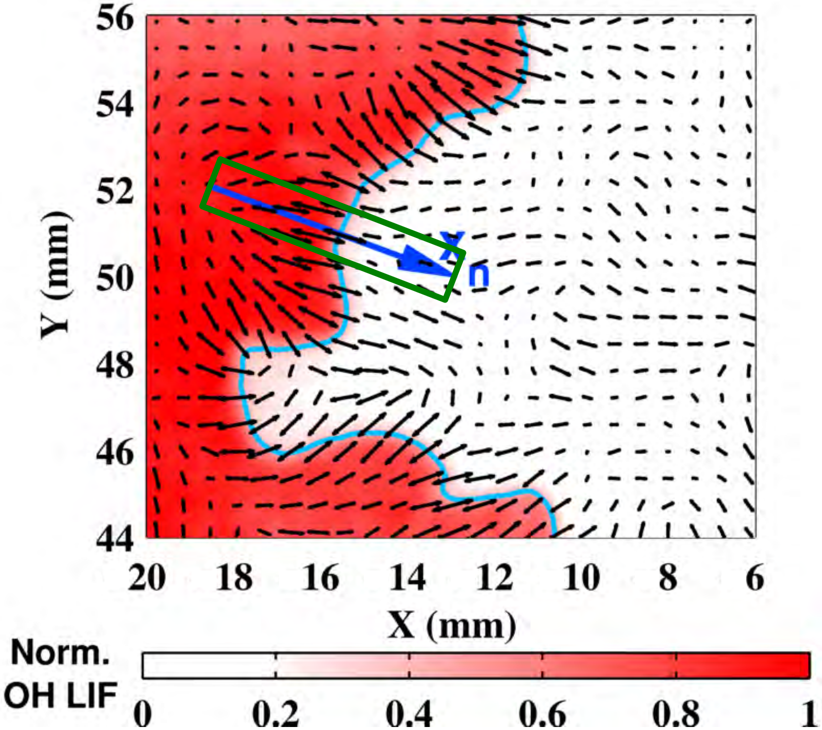

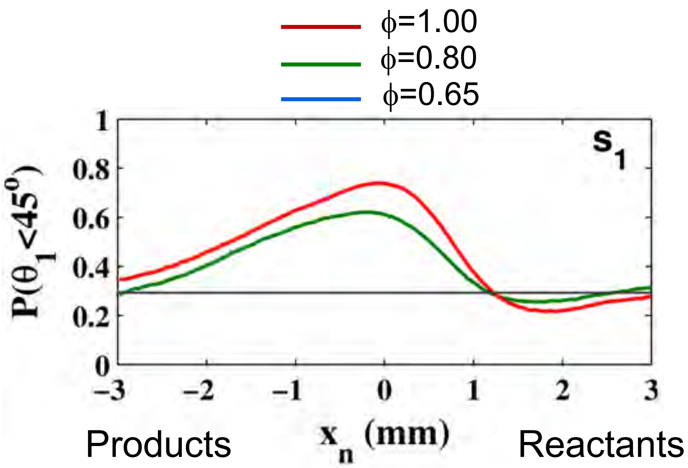

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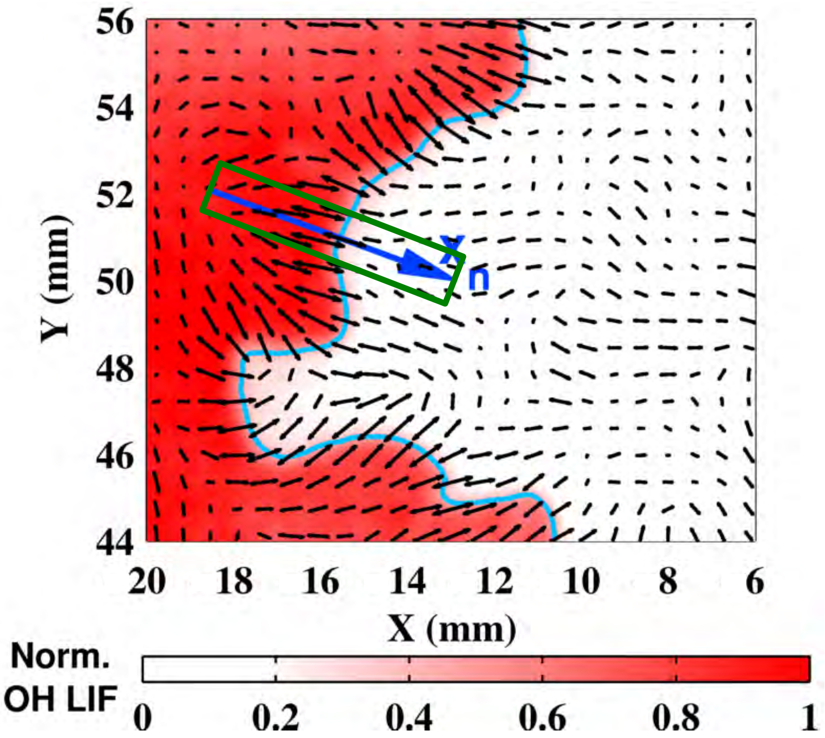

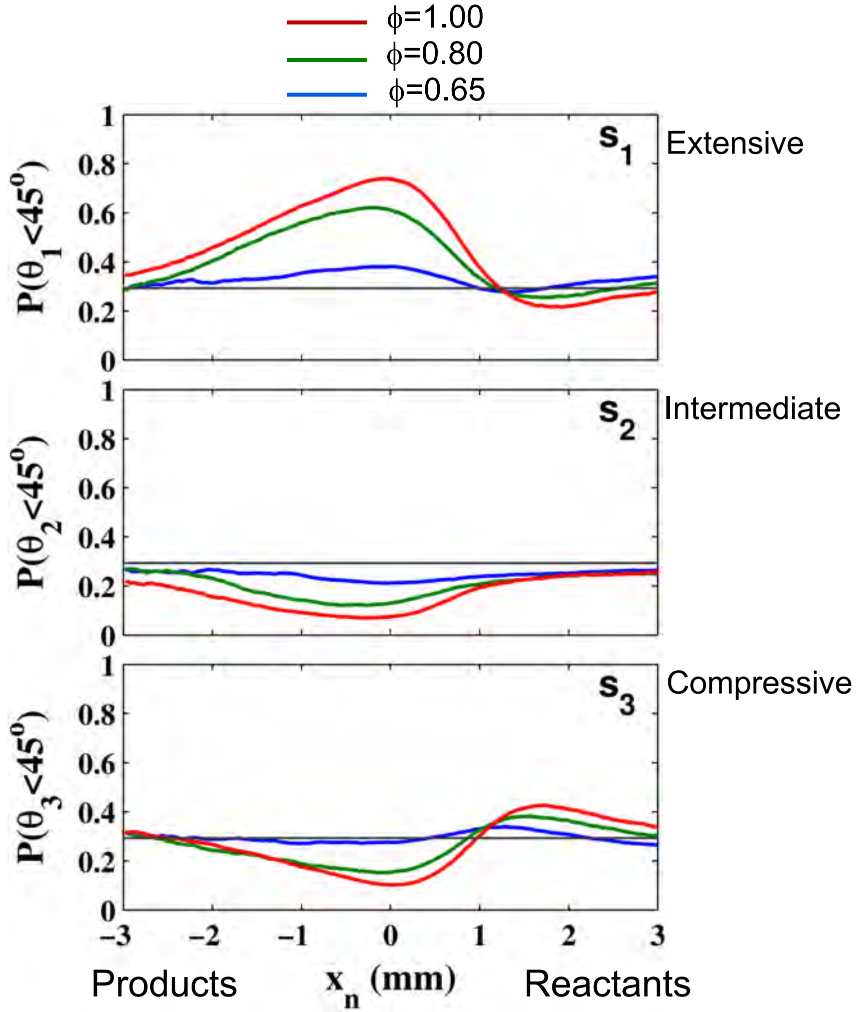

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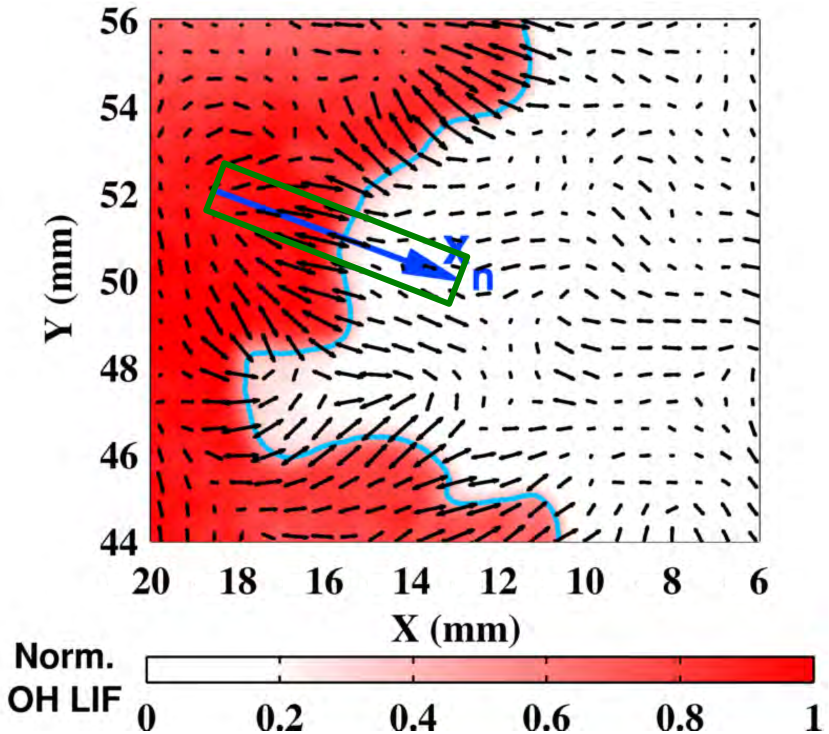

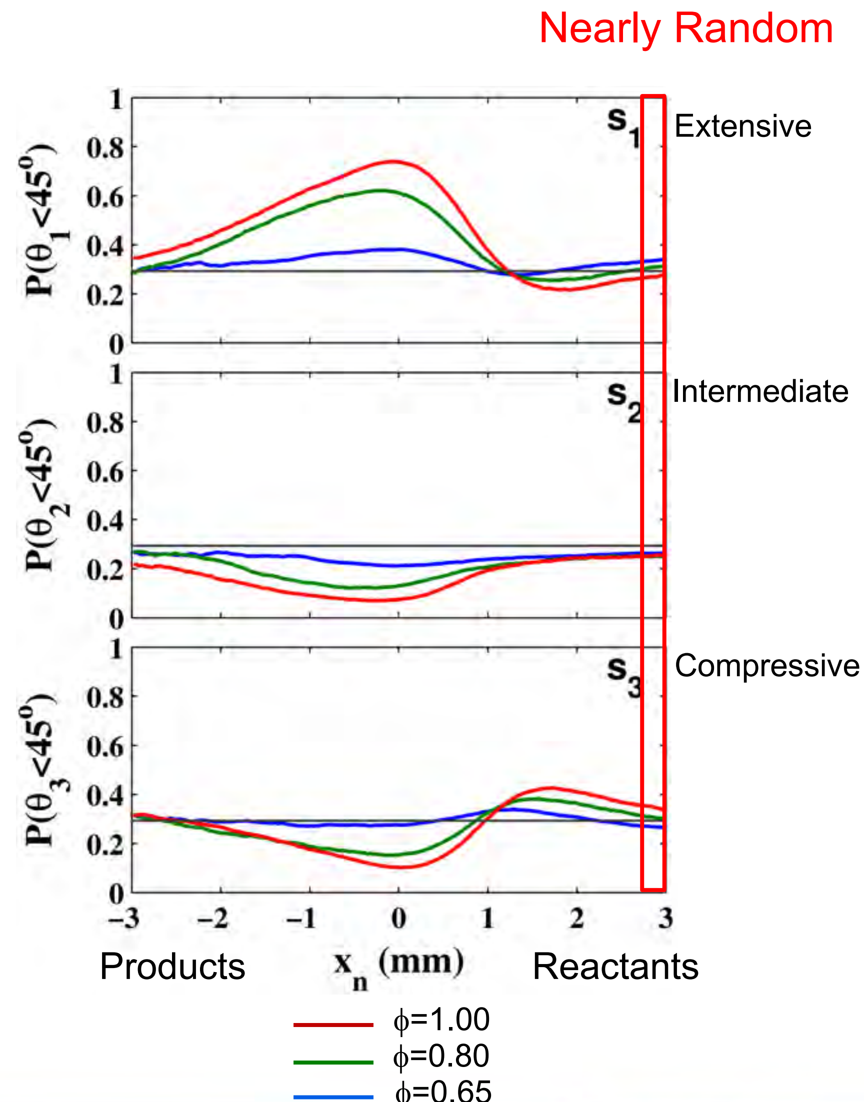

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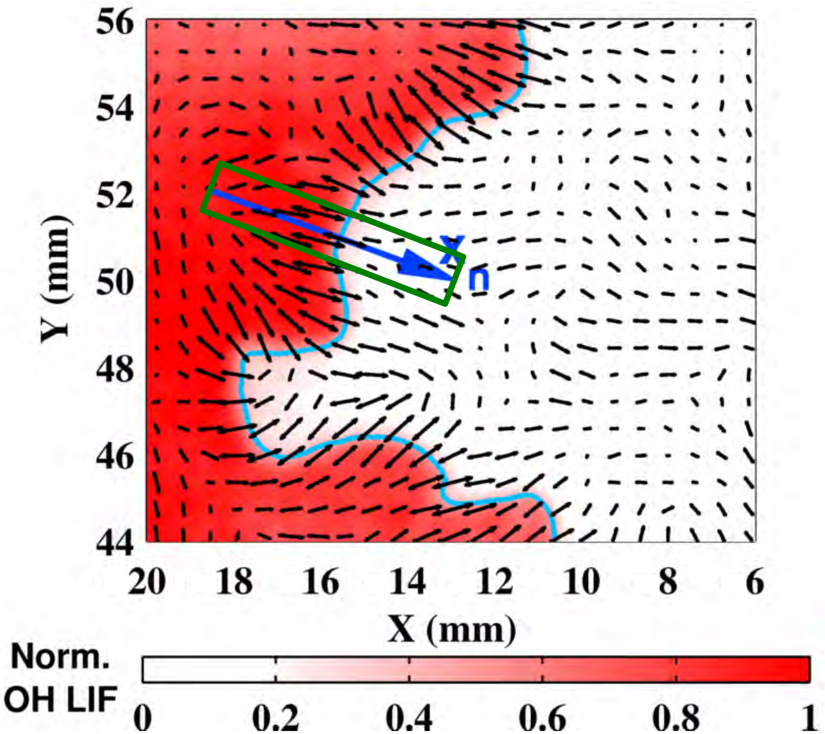

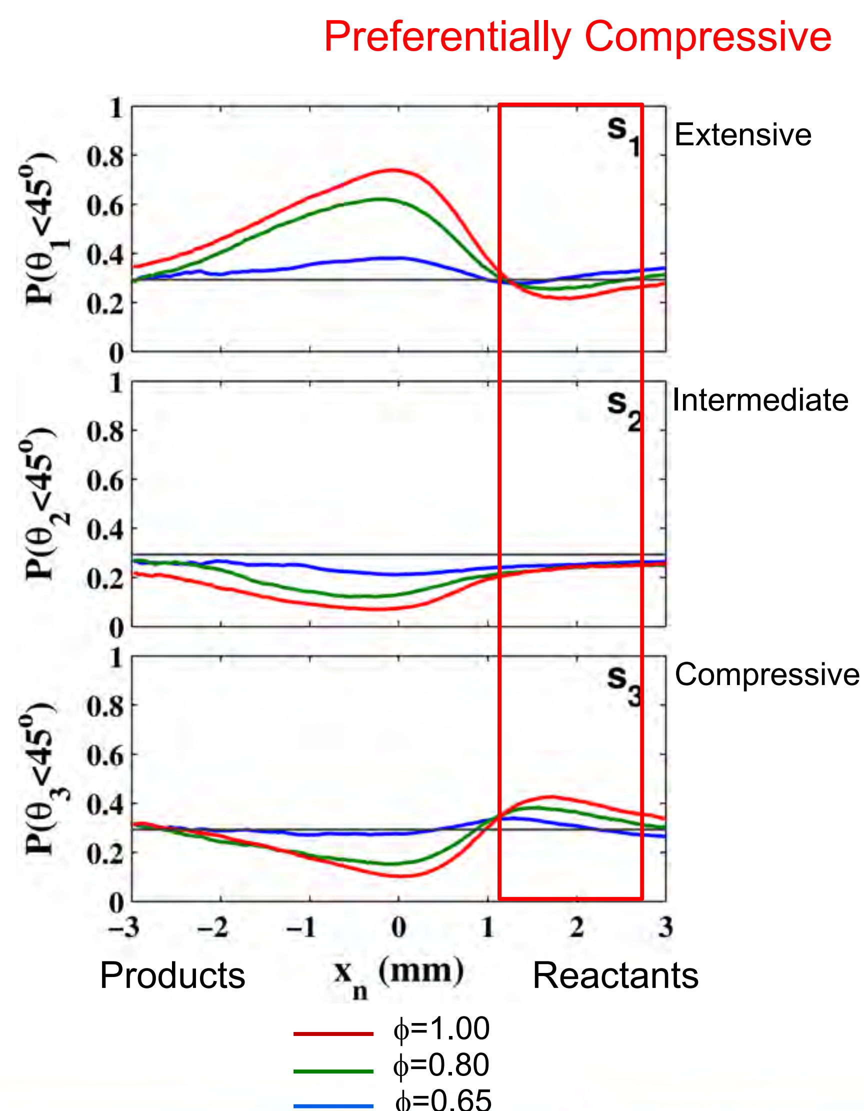

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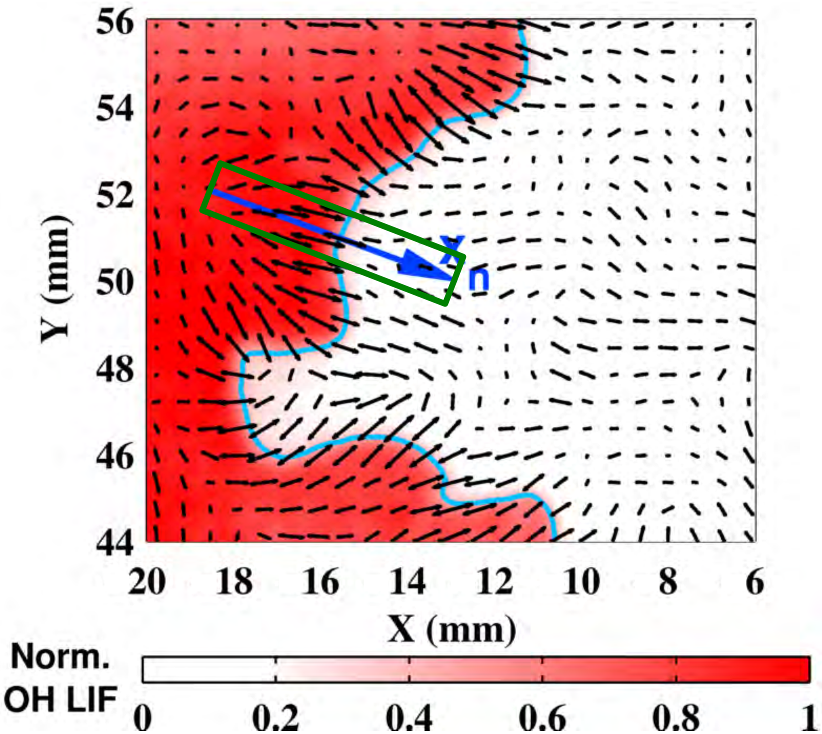

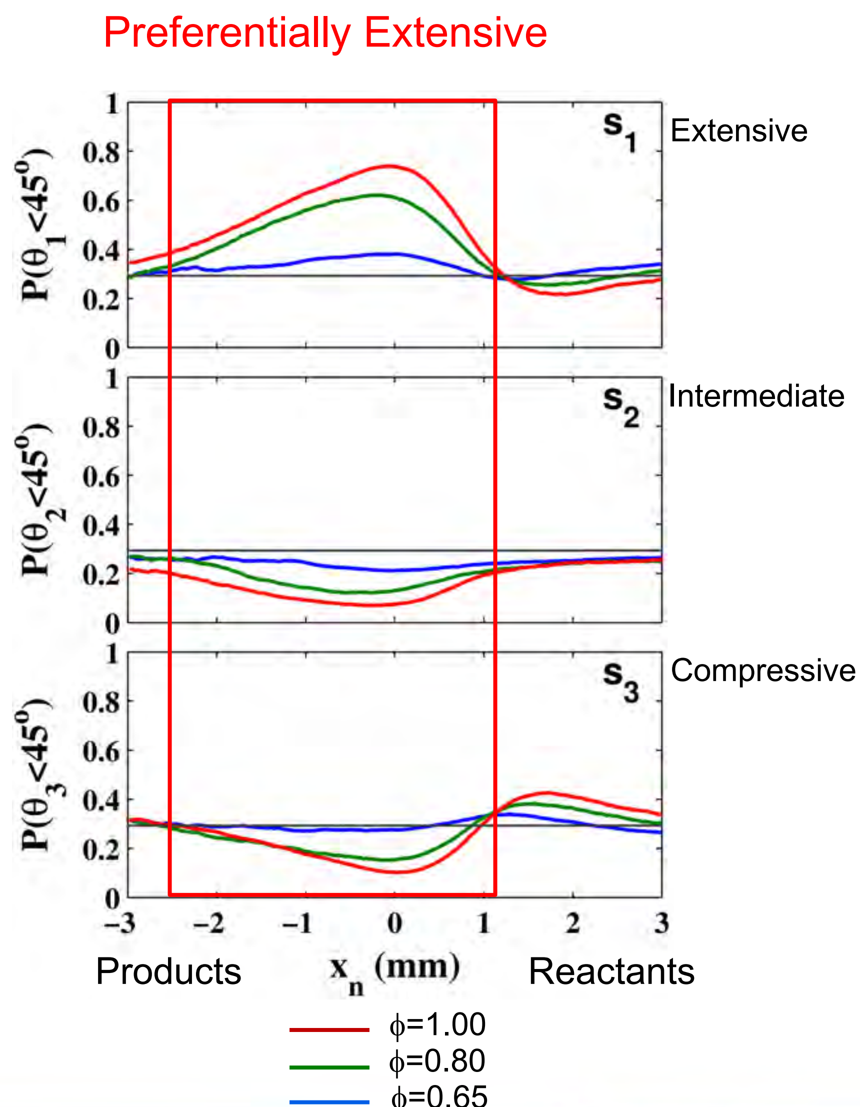

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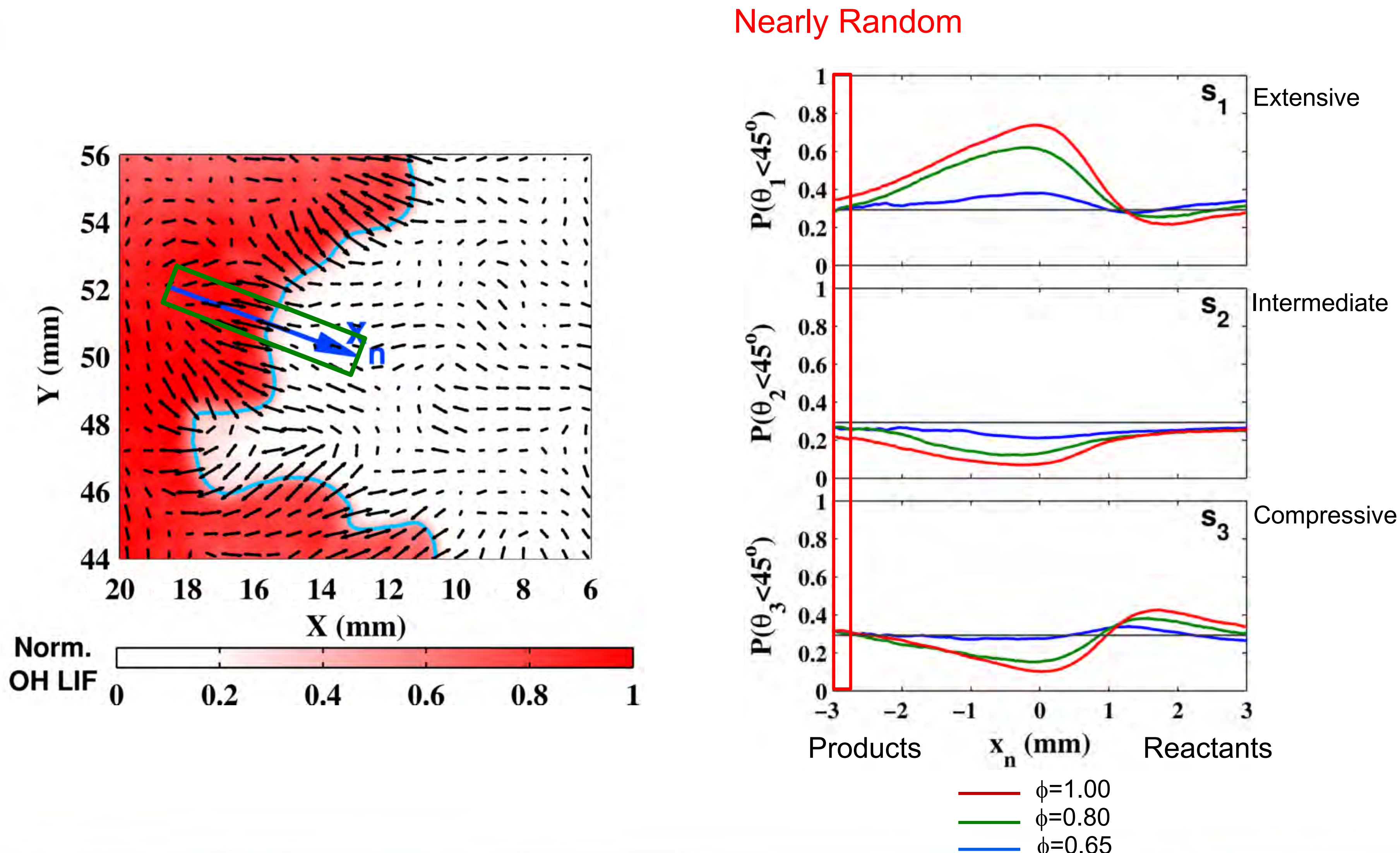
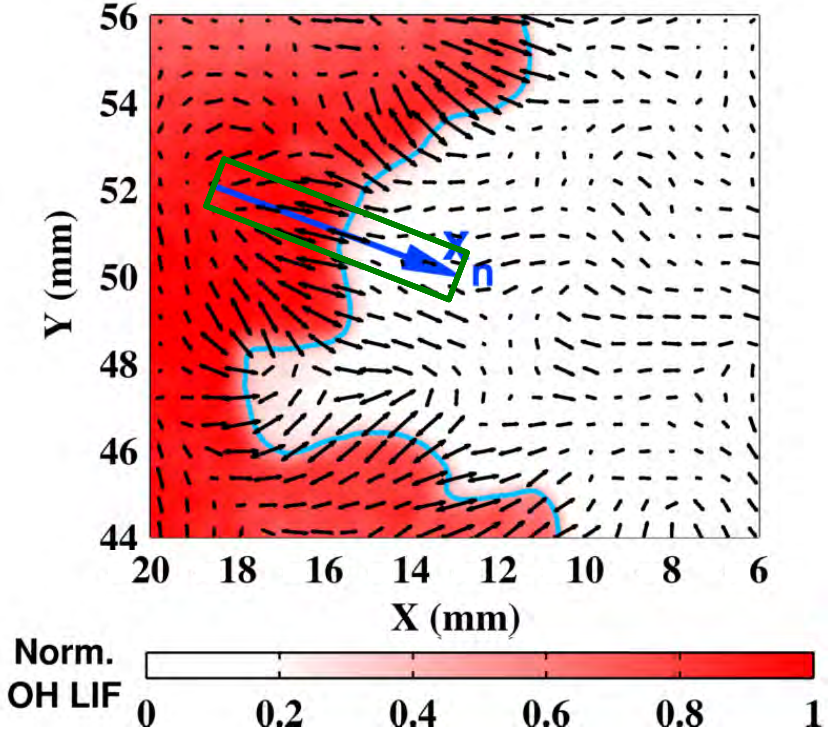
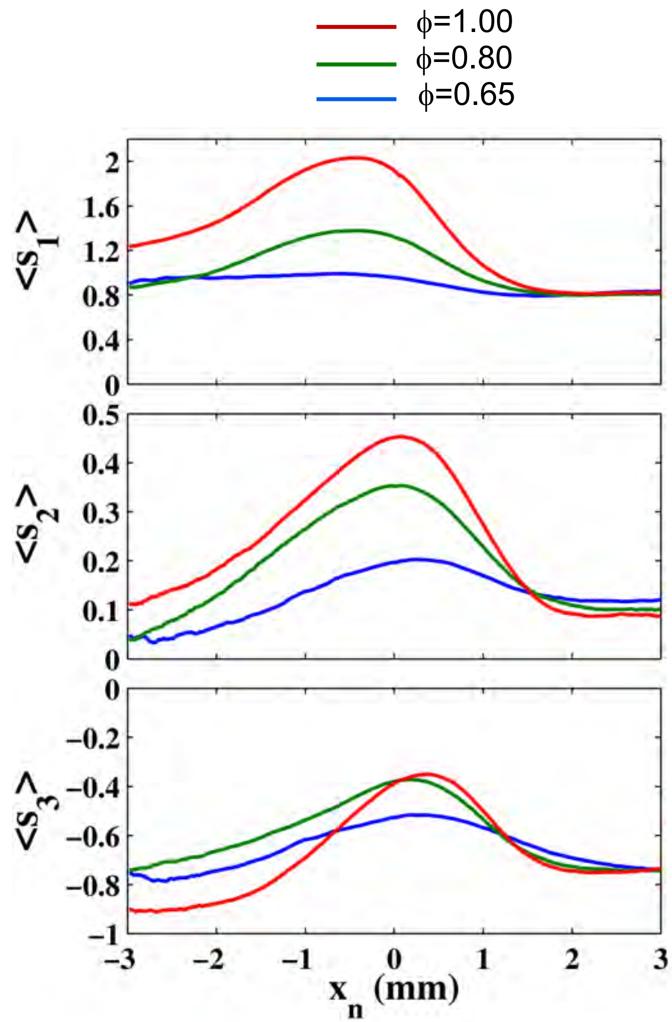
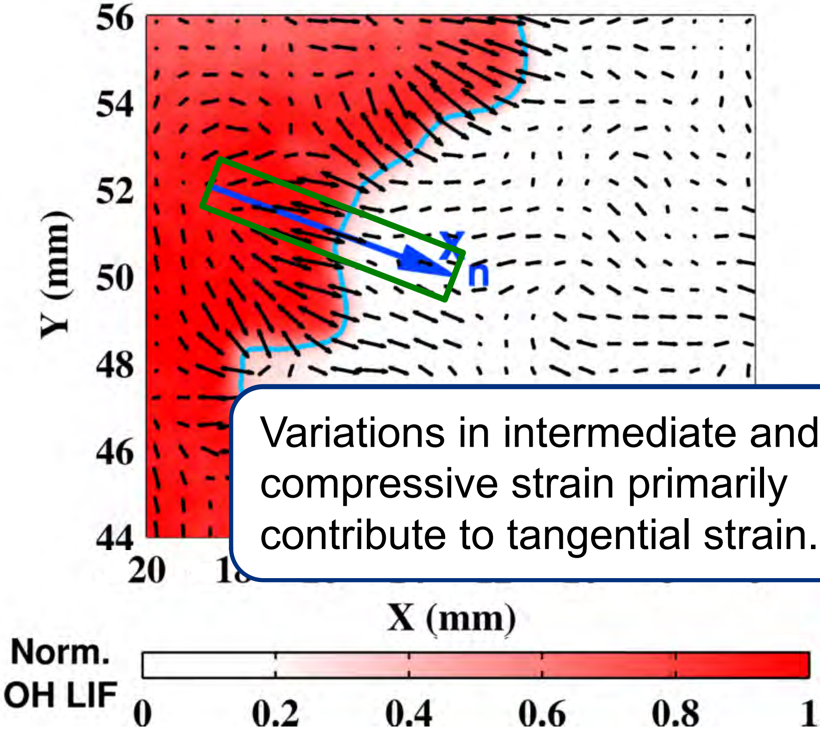


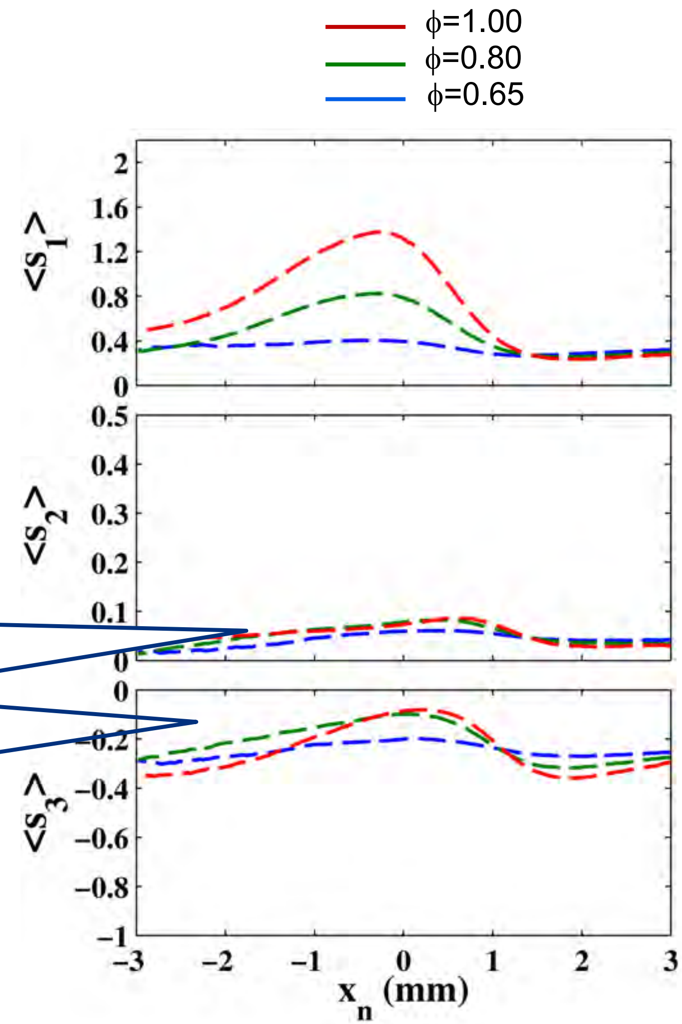
Heat Release Effects on Principal Strain Rates along Flame Normal





Projection of Principal Strain Rates onto Flame Normal Direction

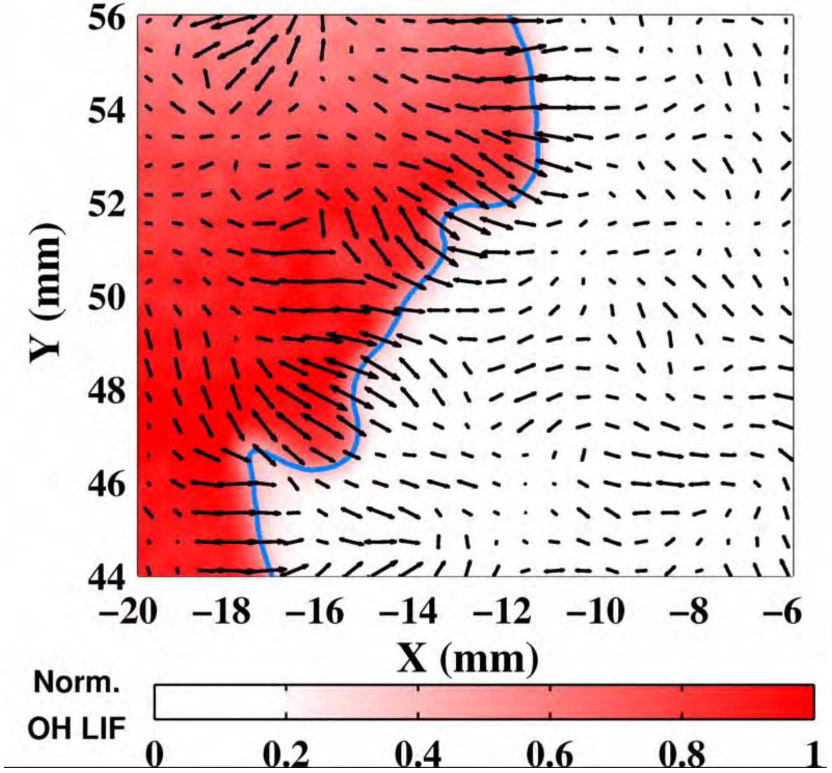




Variations in intermediate and compressive strain primarily contribute to tangential strain.

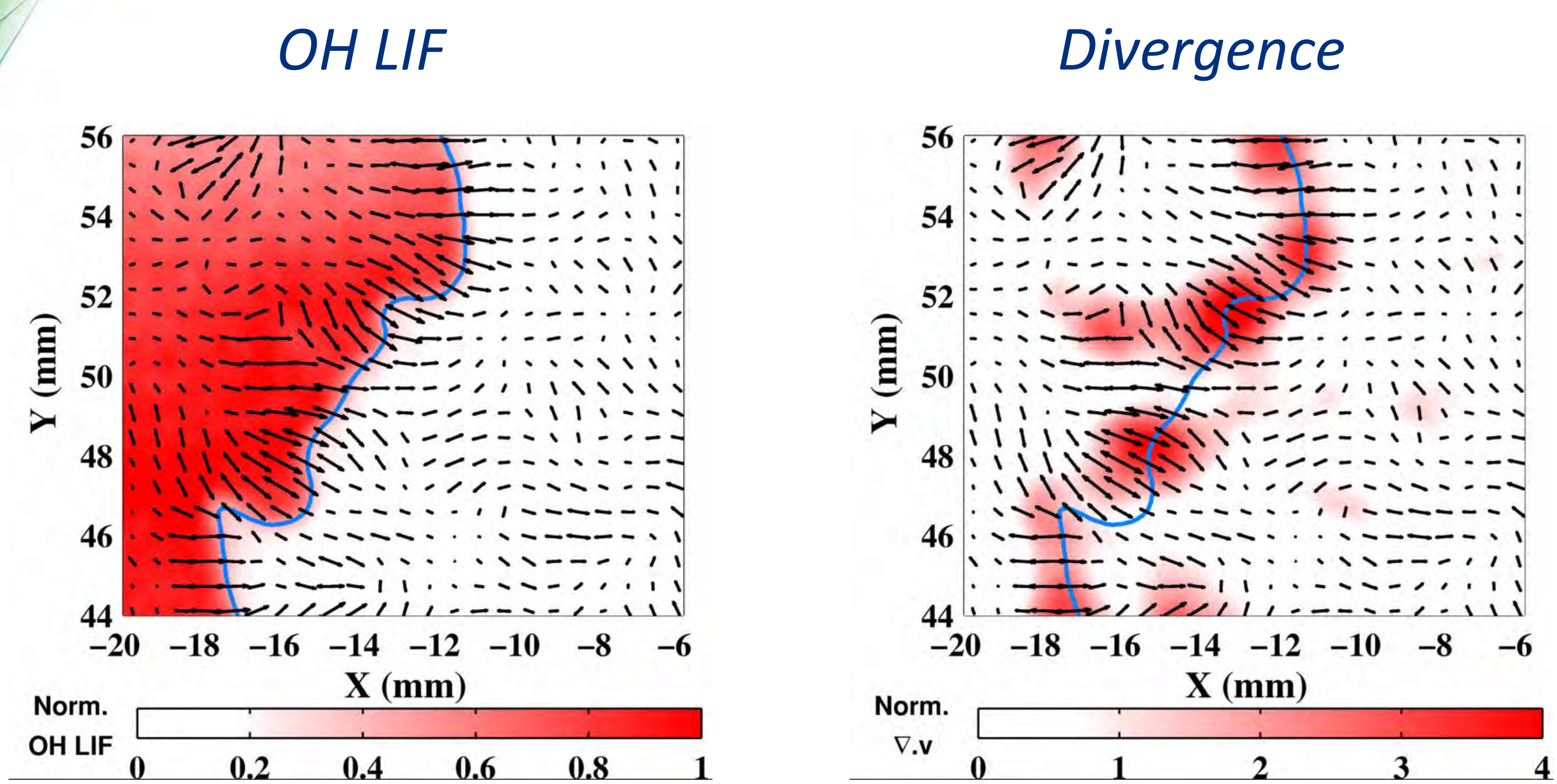
10 kHz Measurement of Extensive Strain Rate Eigenvector Relative to Flame Front

OH LIF



Flame contour (blue line)
Vectors: s_1 axis

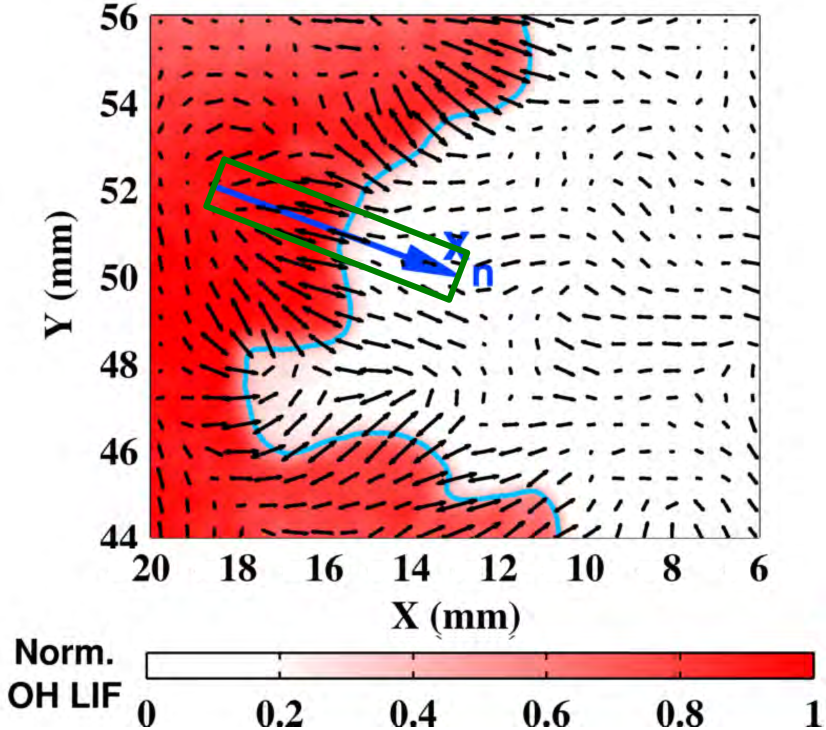
10 kHz TPIV and OH PLIF Recordings

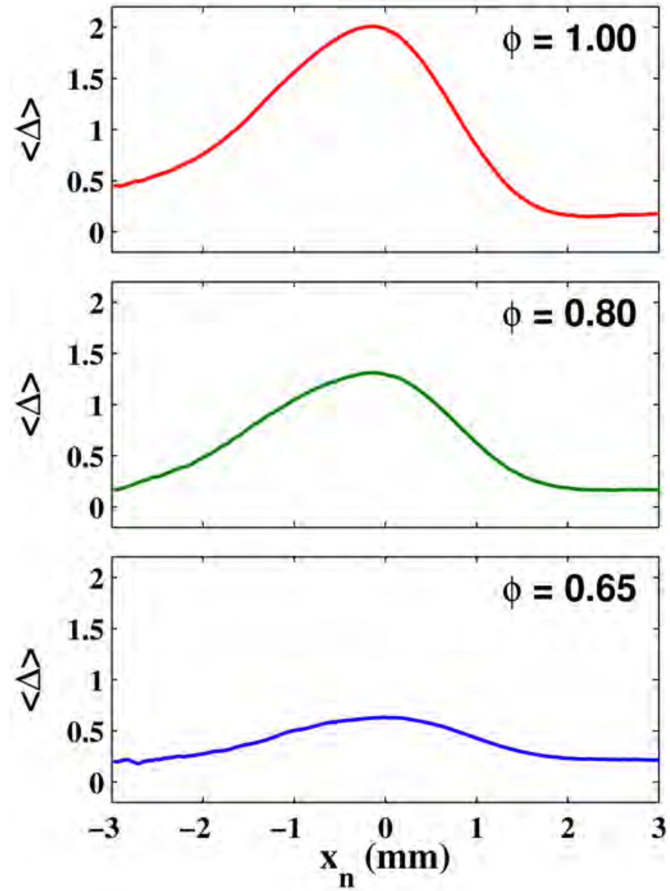


Flame contour (blue line)

Vectors: s_1 axis

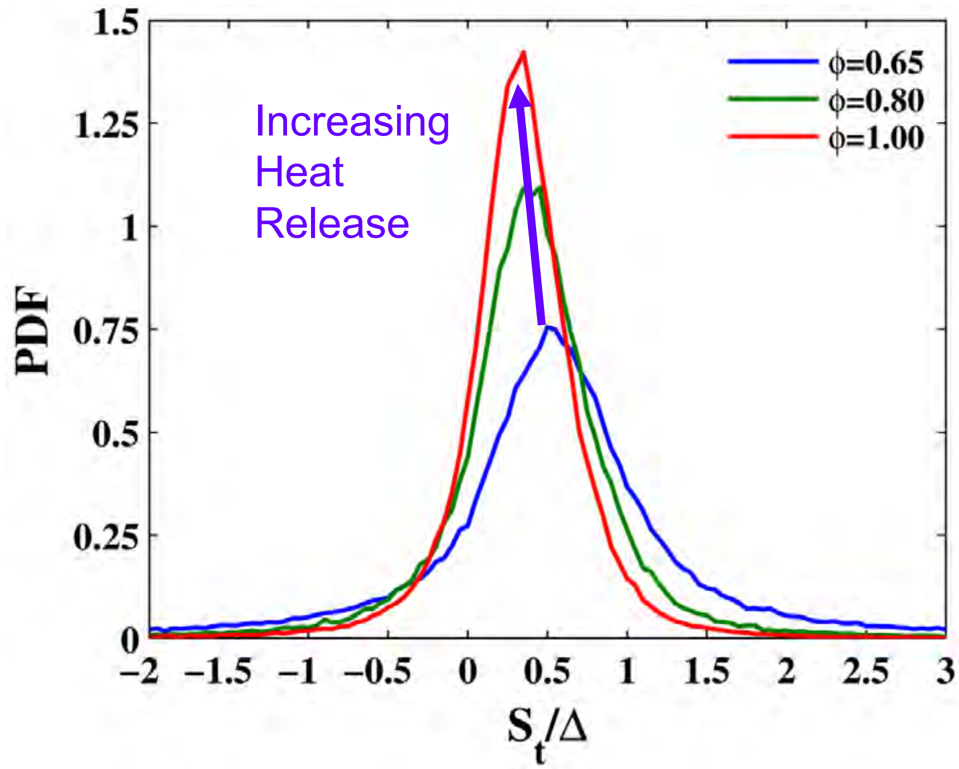
Conditional Mean Profiles of Divergence, Normal Strain, and Tangential Strain





Values normalized by mean strain rate norm in non-reacting flow: $\langle|s|\rangle = 535\ s^{-1}$

Effect of Heat Release on Ratio of Tangential Strain to Divergence at Flame Front



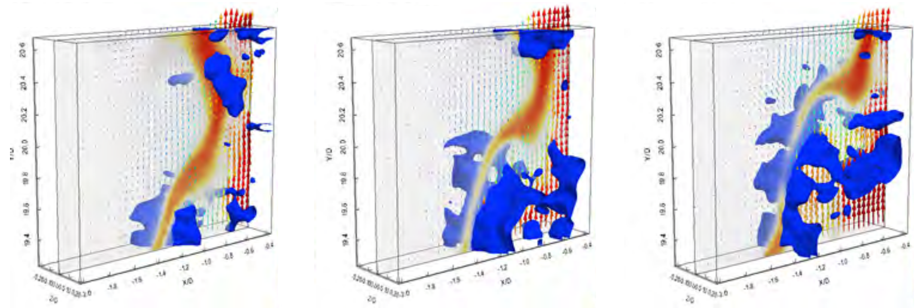
Δ increases more than S_t as a function of heat release.

Summary

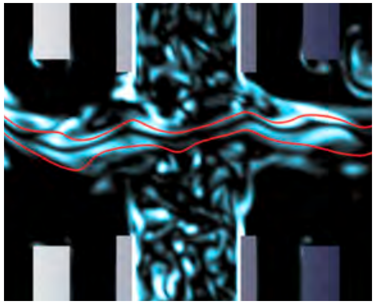
- Divergence and complete strain rate tensor measured in turbulent premixed flames and corresponding non-reacting flow using Tomo-PIV
- 3-D velocity field + OH-LIF imaging used to evaluate preferential alignment of principal strain rates relative to flame-normal direction
- Progression of local strain rate alignment with flame normal
  - Nearly random orientation 3 mm on either side of flame front
  - Compressive strain favored 1-3 mm on reactant side
  - Extensive strain favored in ~3 mm region straddling flame front
- Determined degree of heat release dependence for divergence, normal strain, and tangential strain – implications for transport equations

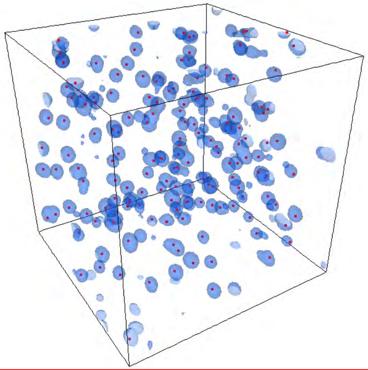
Outline

3-D Measurements of Flow Fields in Turbulent Flames

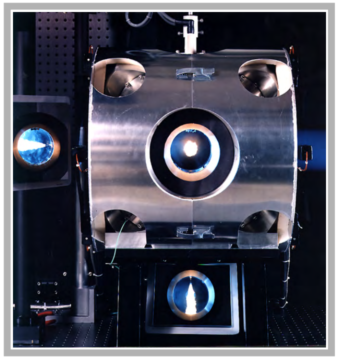


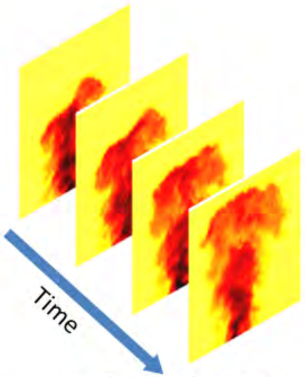
Coupling Tomo-PIV with Large Eddy Simulations





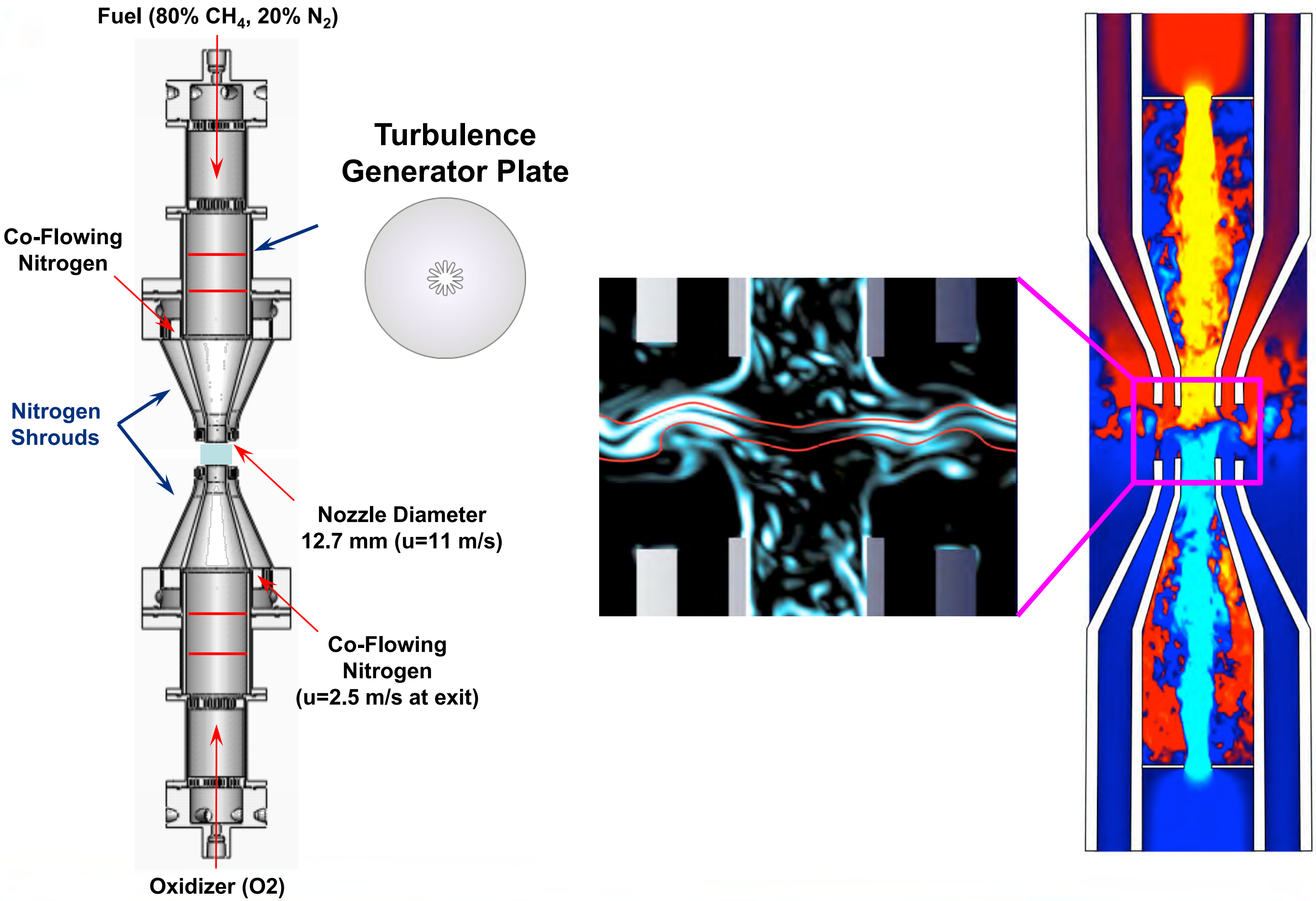
Imaging High-Pressure Fuel Injection Dynamics with Pulse-Burst Laser



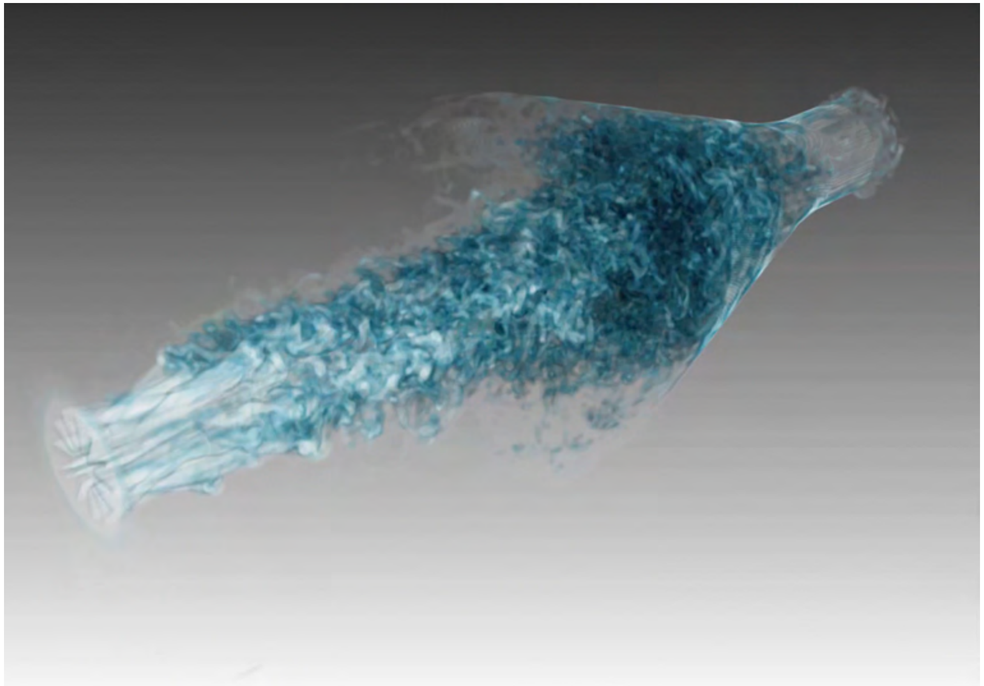


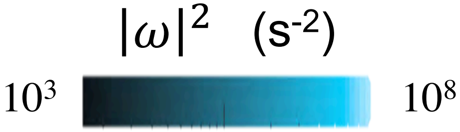
Coupling Experiments and Simulations

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



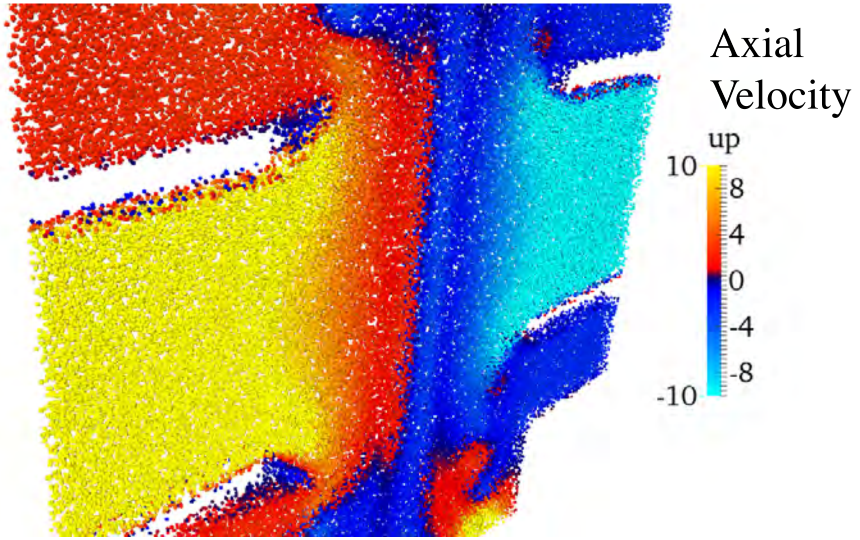
Full LES Domain Simulates Internal Flow Through Turbulence Generator Plate





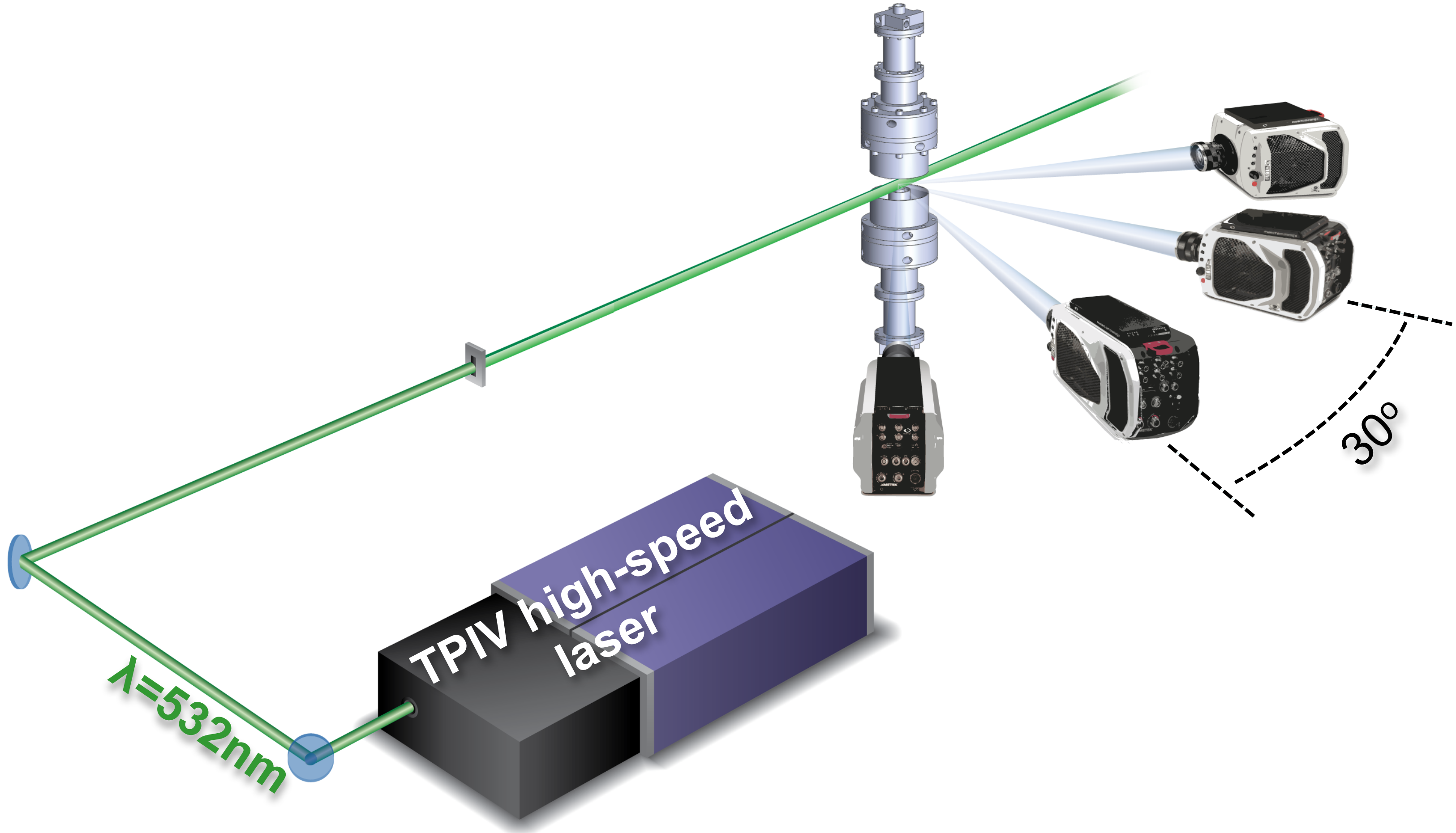
Parametric Studies of Tomo-PIV Uncertainty using Synthetic Particles in Counterflow

60 particles/mm^3



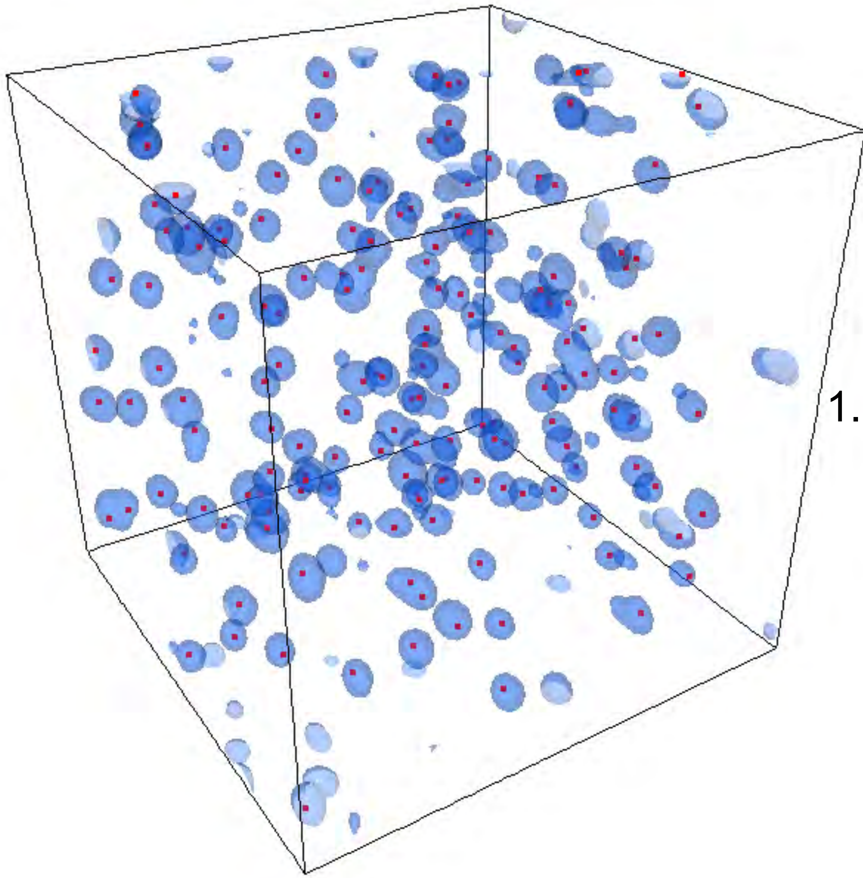
- Particles introduced after 10-20 flow-through times
- Aluminum oxide particles (d = 0.3 um)
- Trilinear interpolation used to calculate velocity of each particle
- LES cell size = 450 um
- Tomo-PIV interrogation window = 413 um.

Emulate Experimental Configuration with Synthetic Tomographic Projections



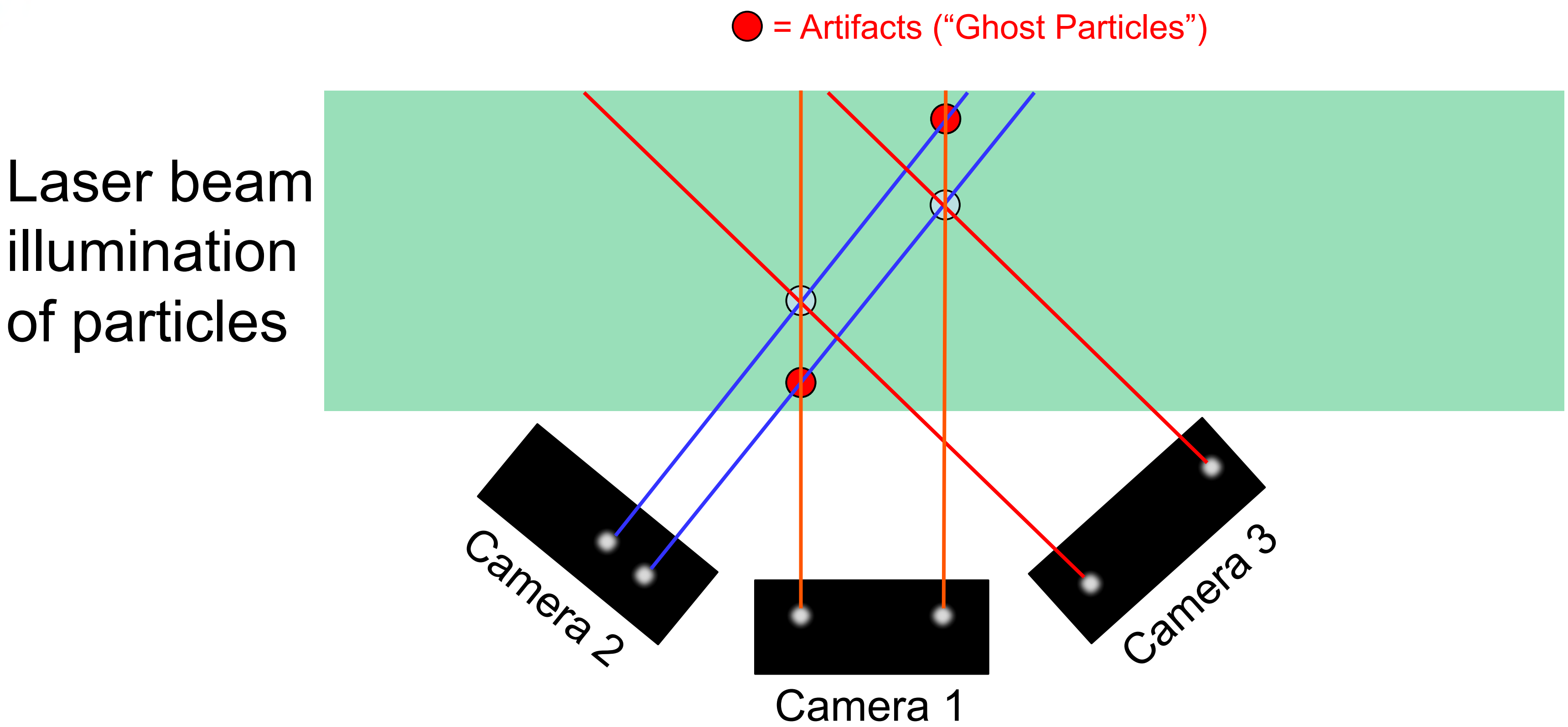
Subset of Reconstructed Particle Field

Low
Seed
Density



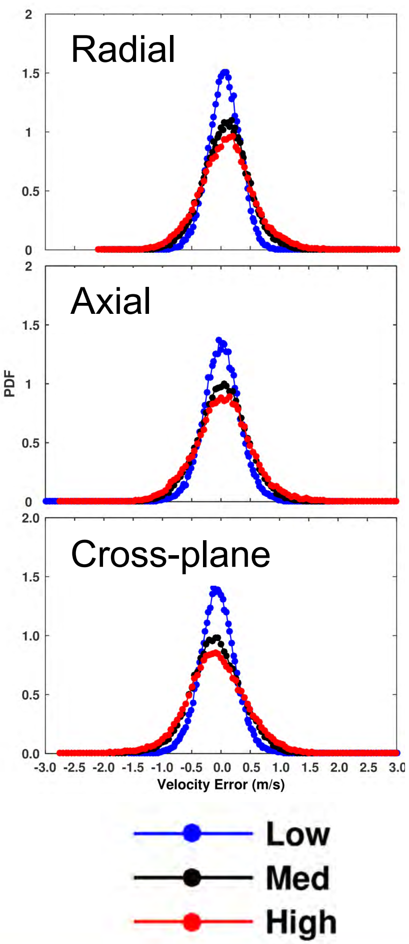
- Red dots = actual particle locations from LES
- Blue regions = tomographic reconstruction
- Ghost particles = blue regions without red dots

Source of Artifacts in Tomo-PIV

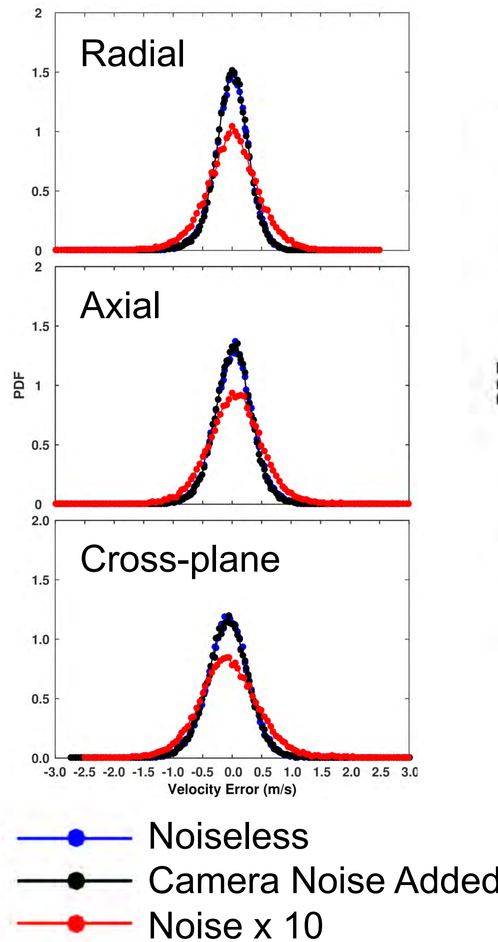


Parametric Studies of Uncertainty

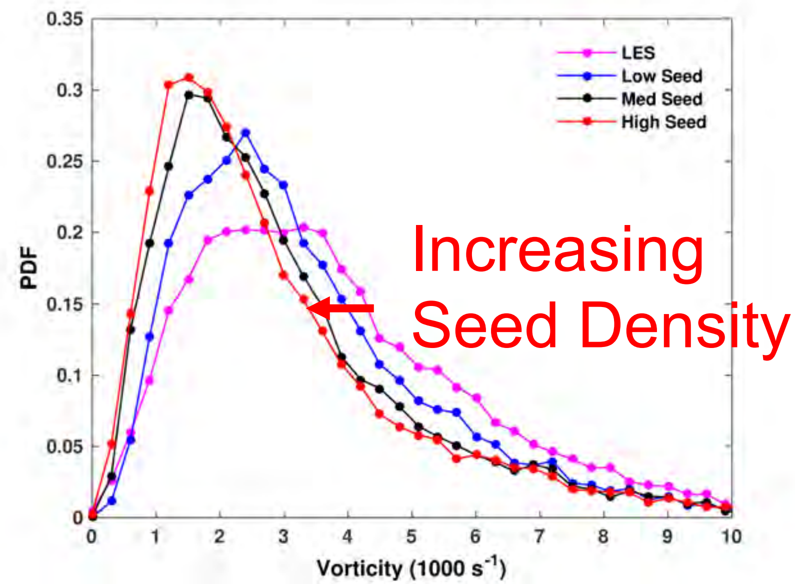
Particle Number Density



Detector Noise



Effect of Particle Number Density on Vorticity Magnitude



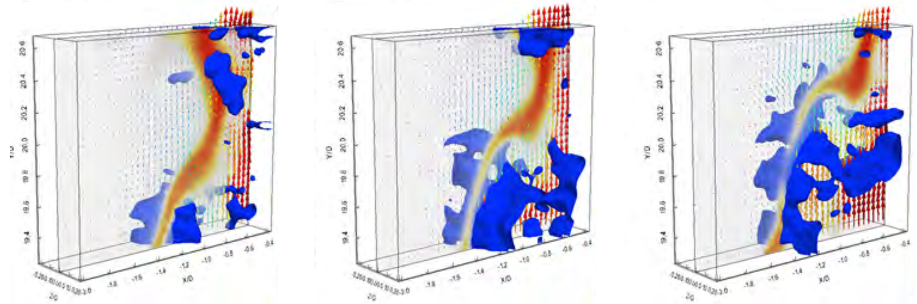
$$\boldsymbol{\omega} = \nabla \times \boldsymbol{V}$$

Summary
LES Evaluation of Tomographic PIV

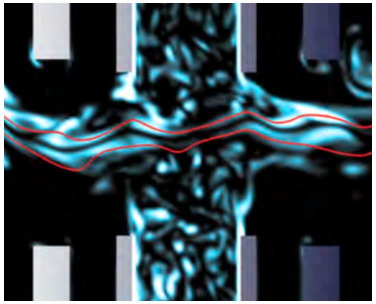
- Parametric numerical studies to assess uncertainties and improve Tomo-PIV processing in reacting flows
- Future investigations: RAPTOR code to simulate Tomo-PIV measurements using LES to near-DNS
- Uncertainty quantification analysis
- Ultimately, improve understanding of feedback between chemical reactions and physics of turbulence

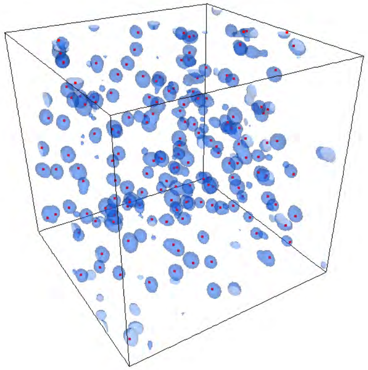
Outline

3-D Measurements of Flow Fields in Turbulent Flames

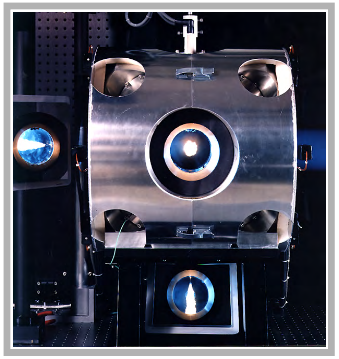


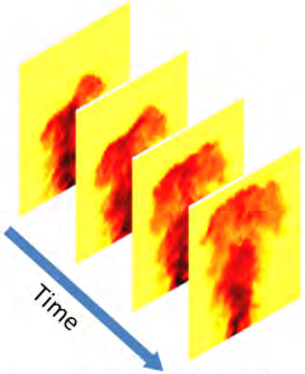
Coupling Tomo-PIV with Large Eddy Simulations



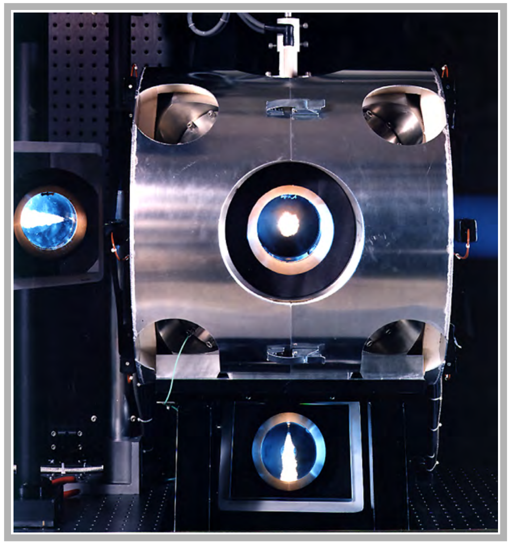


Imaging High-Pressure Fuel Injection Dynamics with Pulse-Burst Laser





Advances in Imaging Diagnostics Applied to High-Pressure Fuel Injection

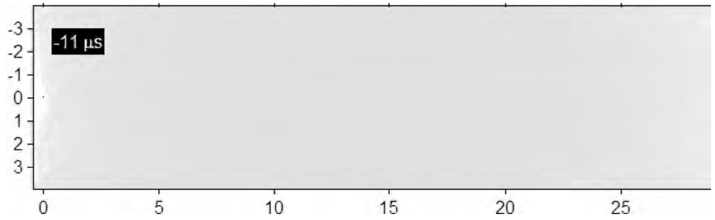


High-Pressure Fuel Injection
for IC Engines

Previous Imaging Capabilities

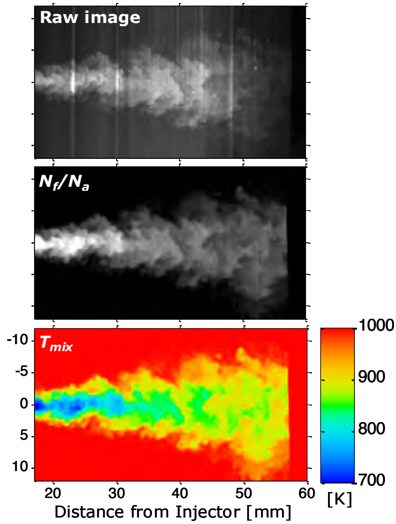
Line-of-sight Measurements

- Limited diagnostic techniques
- Difficult to interpret



Single-shot planar imaging

- Missing insight into dynamics



Need high-speed planar imaging capability and improved high-pressure diagnostics

Diesel Ignition/Combustion Linked to Transient Mixing

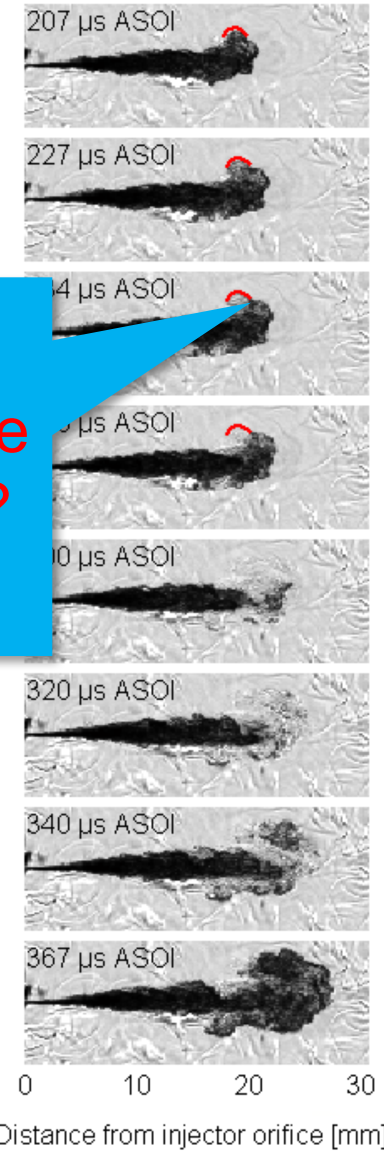
Diesel "Spray A" conditions

Ambient Gas
900 K
60 bar
15% O_2

Fuel
373 K
1500 bar
n-dodecane
90 μm noz

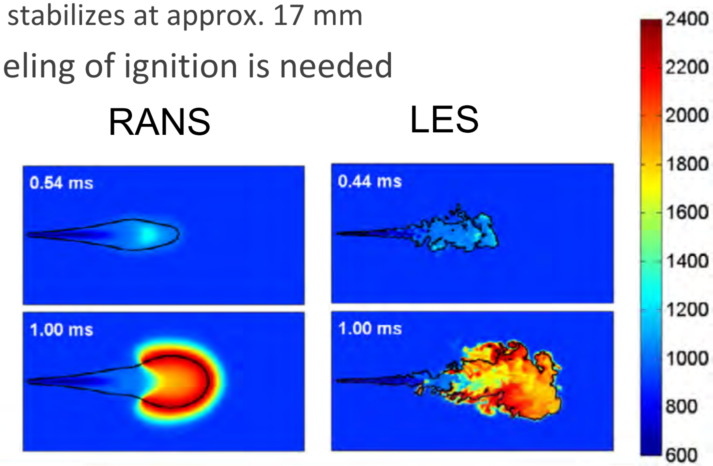
150 kHz schlieren imaging

Schlieren



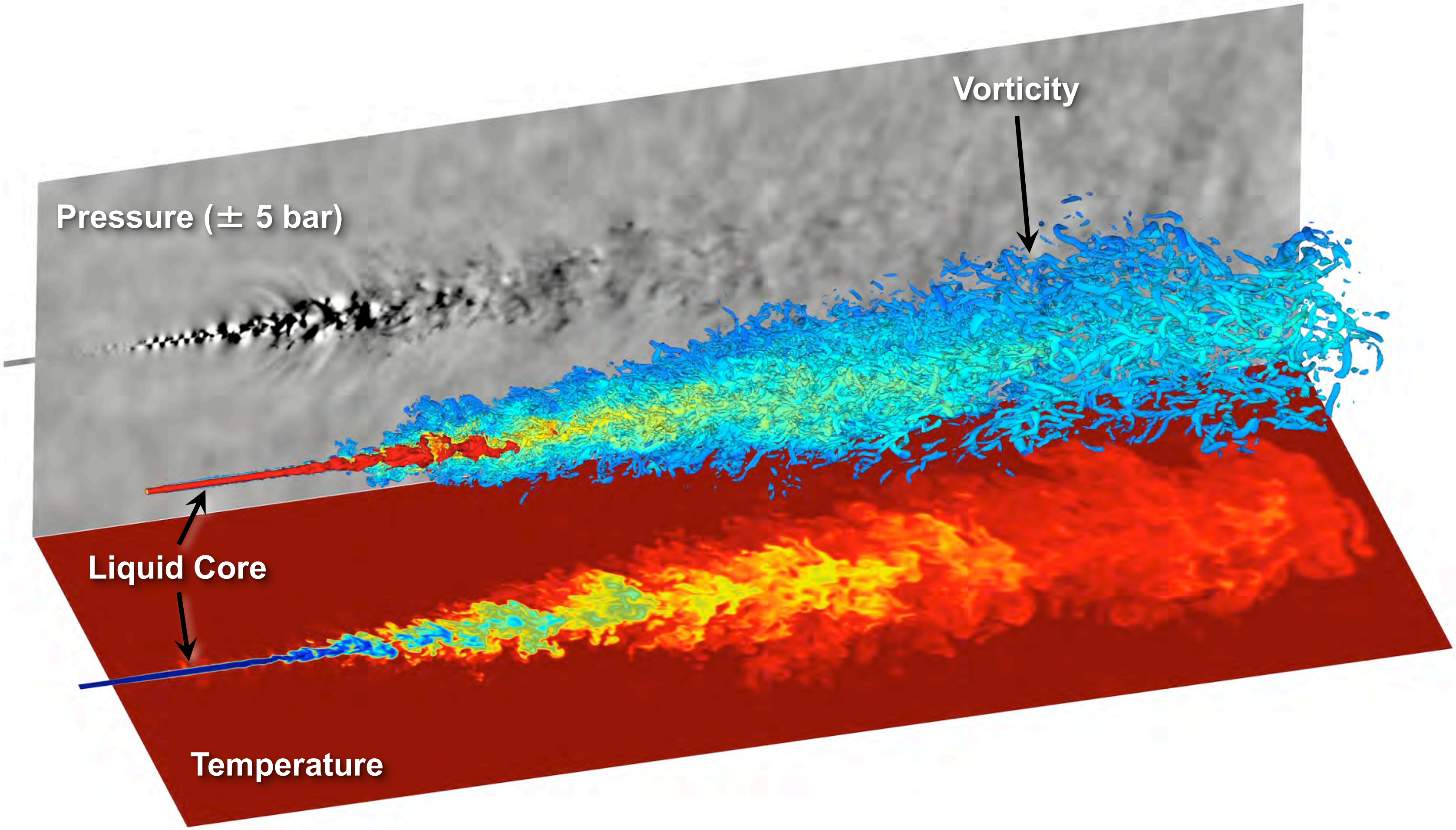
How does local mixture state evolve prior to autoignition?

- Cool flame initiates in rad
  - Schlieren "transparency
    scale organization
  - Cool flame temperature
- High-temperature ignitio
  - 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 in press

Transient Evolution of Jet Shows Detailed Structural Flow Interactions

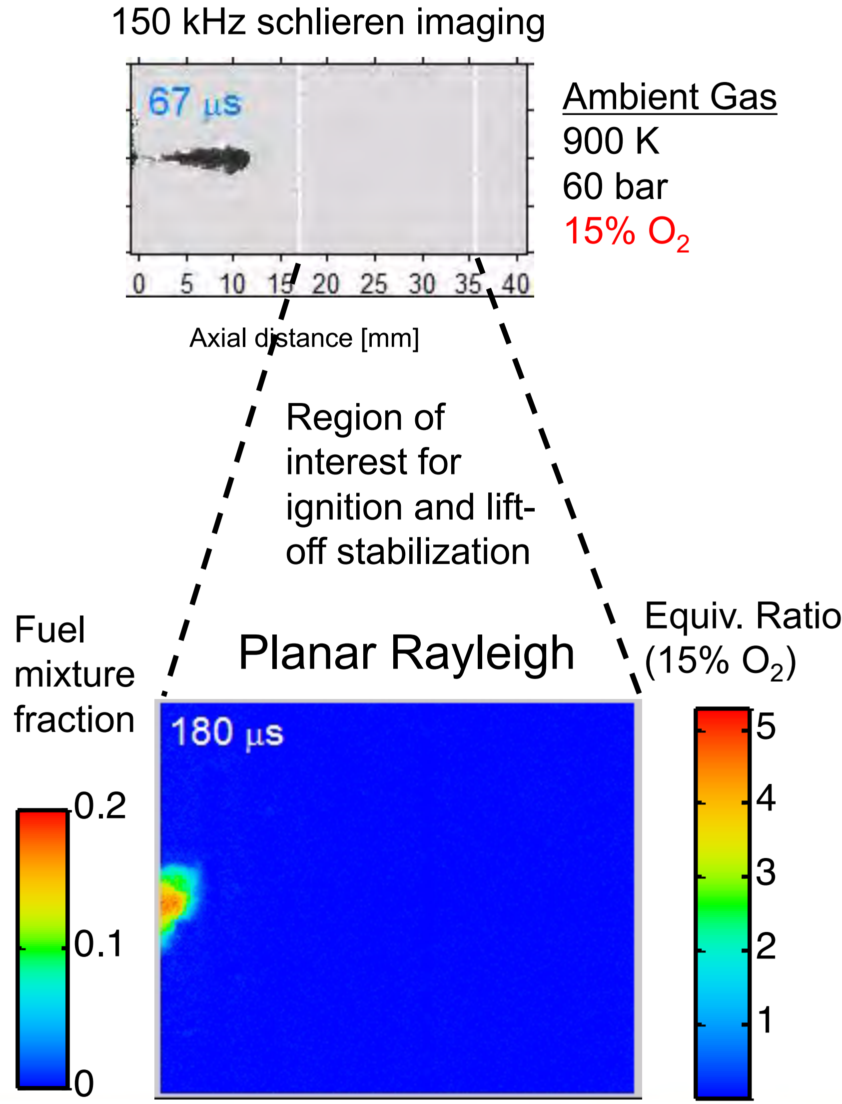


Large Eddy Simulation by Joe Oefelein, Guilhem Lacaze

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
- Jet mixing - large structures shed to side and re-entrained
  - Larger residence time in hot mixtures
- Target for high-fidelity LES studies
  - Verify accurate mixing field as preliminary step towards predicting ignition/combustion
  - Quantify variance, needed input for CFD

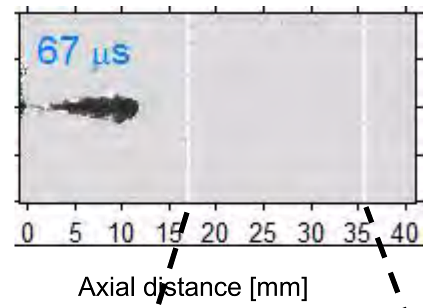
Ambient Gas
900 K
60 bar
0% O_2



Transient Temperature History Important for Ignition

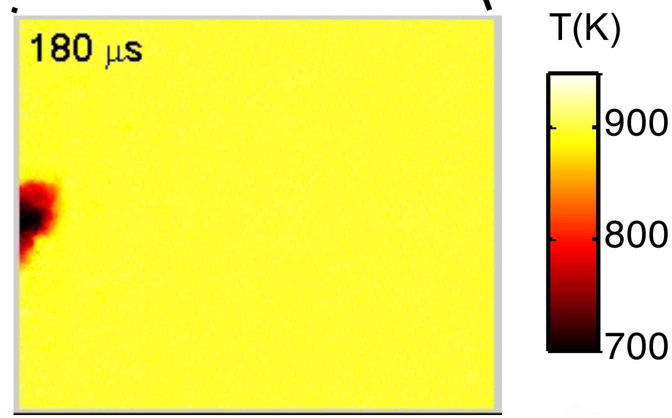
- Rayleigh imaging quantifies transient mixture fraction / equivalence ratio for the first time
  - Target condition Spray A has massive research effort to understand engine spray combustion
- Jet mixing - large structures shed to side and re-entrained
  - Larger residence time in hot mixtures
- Obvious target for high-fidelity LES studies
  - Verify accurate mixing field as preliminary step towards predicting ignition/combustion
  - Quantify variance, needed input for CFD

150 kHz schlieren imaging



<u>Ambient Gas</u>
900 K
60 bar
15% O_2

Region of interest for ignition and lift-off stabilization

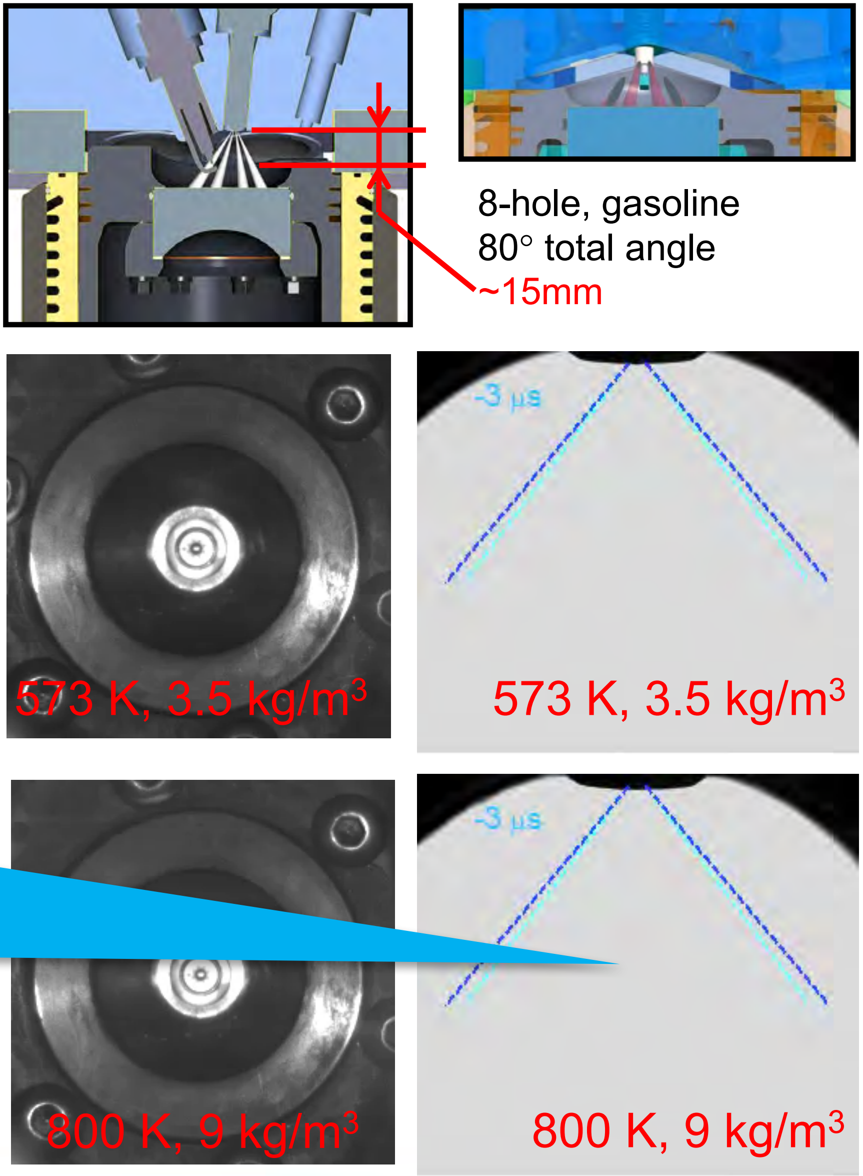


<u>Ambient Gas</u>
900 K
60 bar
0% O_2

Fuel spray mixing is important to efficiency

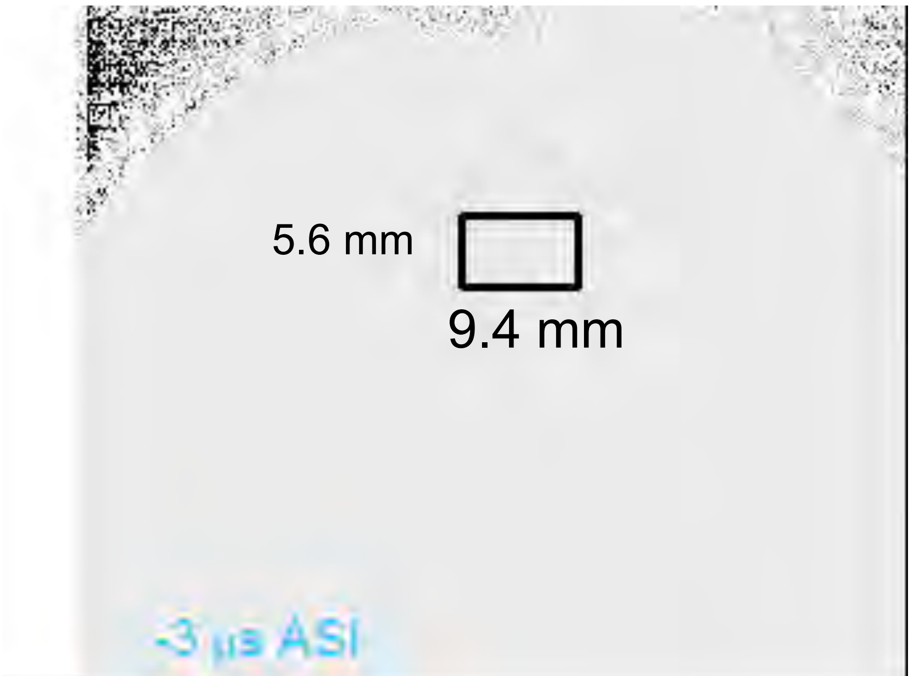
- Barriers for high-efficiency gasoline engines
  - Particulate emissions
  - Engine knock or preignition
  - Slow burn rate or partial burn
  - Heat release control when using compression ignition
  - Lack of predictive CFD tools
- Influence of direct-injection spray
  - Temperature non-uniformities
  - Mixture/flow preparation near spark

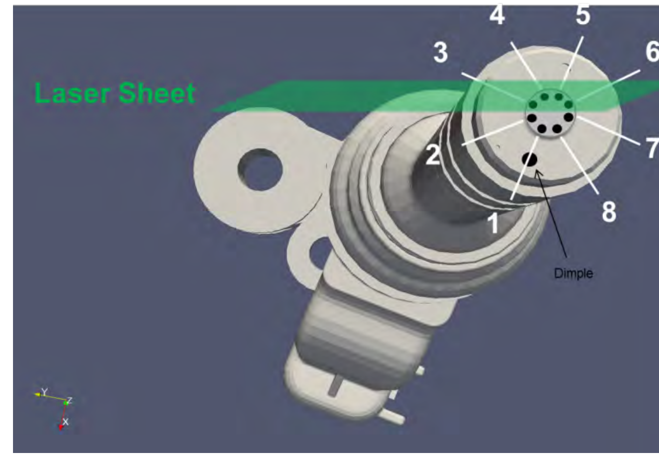
Plume collapse limits mixing of fuel with air.



Velocity measurements using PIV

Measurement plane between plumes to probe critical region





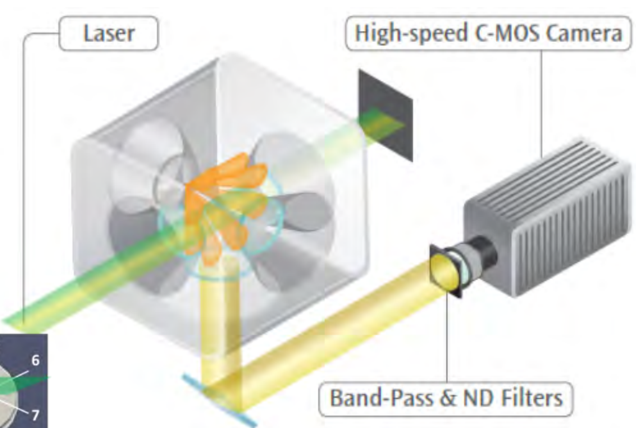
Ambient Gas	Fuel
573 K	363 K
6 bar	200 bar
3.5 kg/m^3	iso-octane
0% O_2	170 μm nozzle

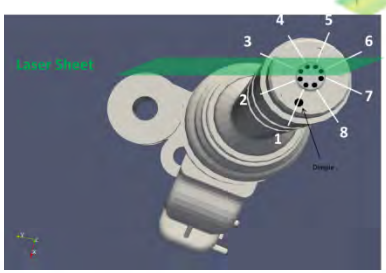
Plumes remain separate during injection but then merge at the end of injection

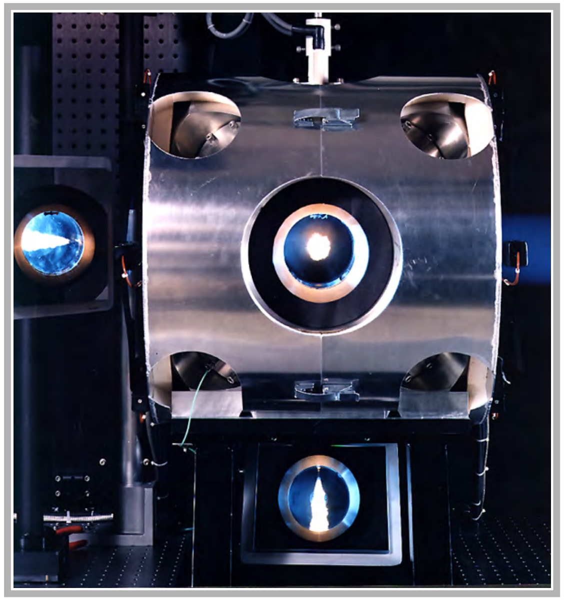
100 kHz PIV Measurements of Flow in Center of Injection Cone

- Custom pulse-burst laser system
  - 100 kHz pulse pairs
  - 500 pulse pairs (5 ms burst)
  - 15 mJ/pulse at 532 nm

- Applied PIV
  - 1 µm zirconia seed in gas phase
  - 200 kHz imaging
  - Liquid-phase avoided by probing between plumes and moving downstream

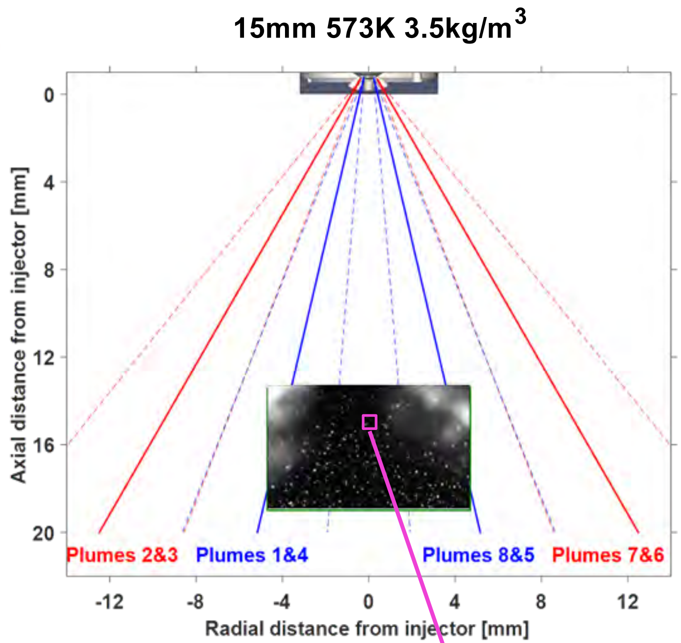




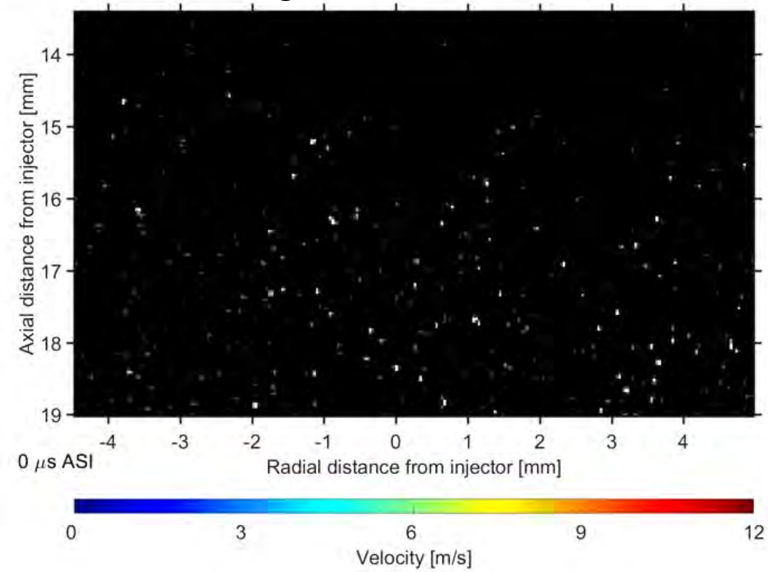


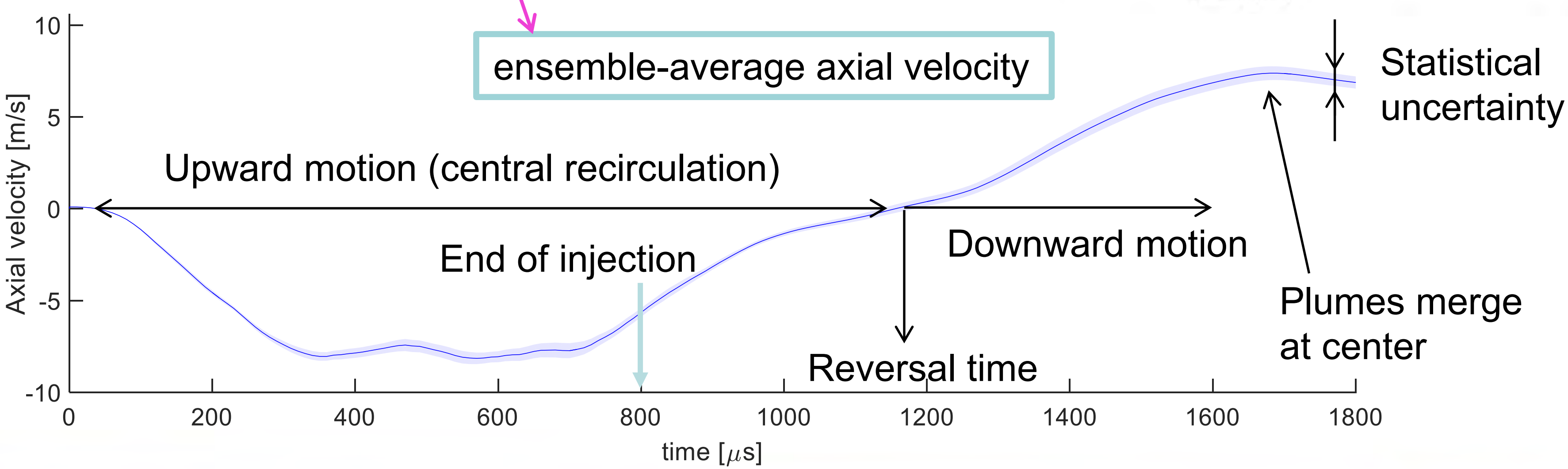
High-Pressure Chamber

Time evolution of velocity between plumes



processed velocity using sliding sum of correlations





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

Acknowledgements

Tomo-PIV, High-Speed Imaging, Pulse-burst Laser Development
Bruno Coriton
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Brian Patterson
Erxiong Huang

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Anthony Ruiz

Engine Research
Lyle Pickett
Scott Skeen
Julien Manin
Panos Sphicas

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Sandia Laboratory Directed Research and Development Program