Application of Laser Diagnostics to the Study of Turbulence – Flame Interactions

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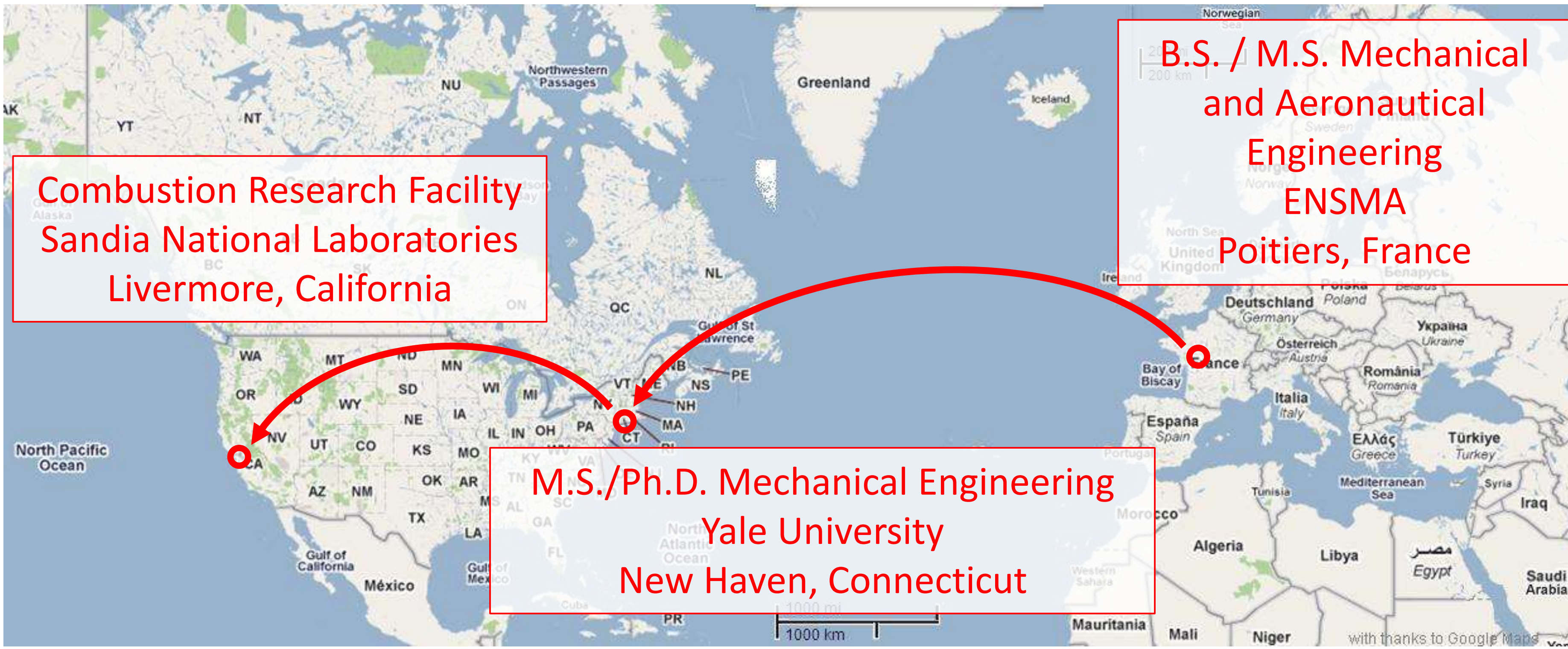
Personal Experience



Outline

I. Introduction and overview of research strategy

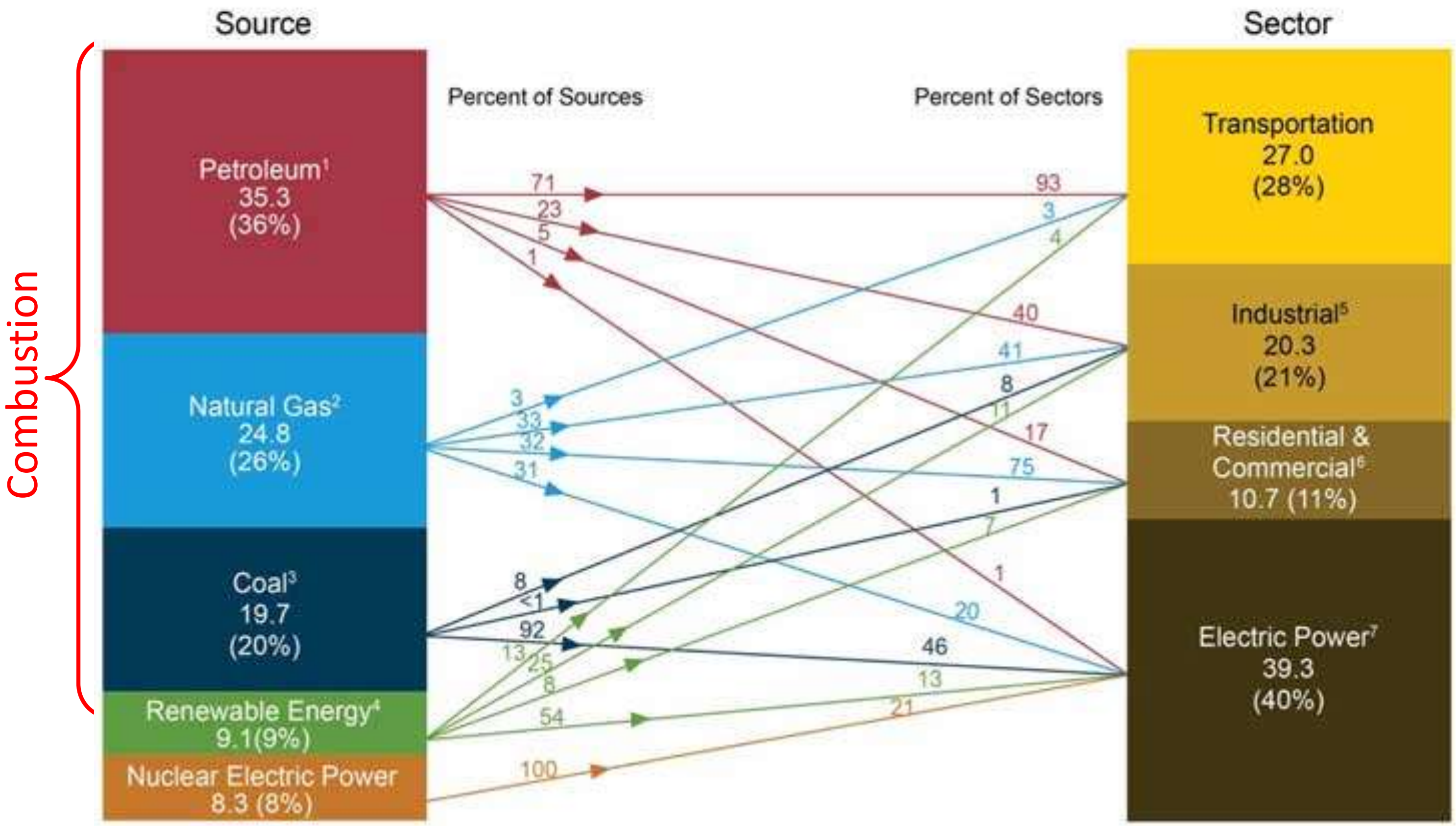
II. Imaging of reaction rates in turbulent counterflow premixed flames

III. High-speed 3D velocity measurements for the study of localized extinctions

IV. Concluding remarks

Combustion Energy Usage

- > 80% of world energy is provided by combustion (~75% in Switzerland).
- Used in all sectors (transportation, chemical processes, electricity production, home appliances, etc).



Source: Annual Energy Review, 2011, EIA

Combustion Energy Usage

Challenges

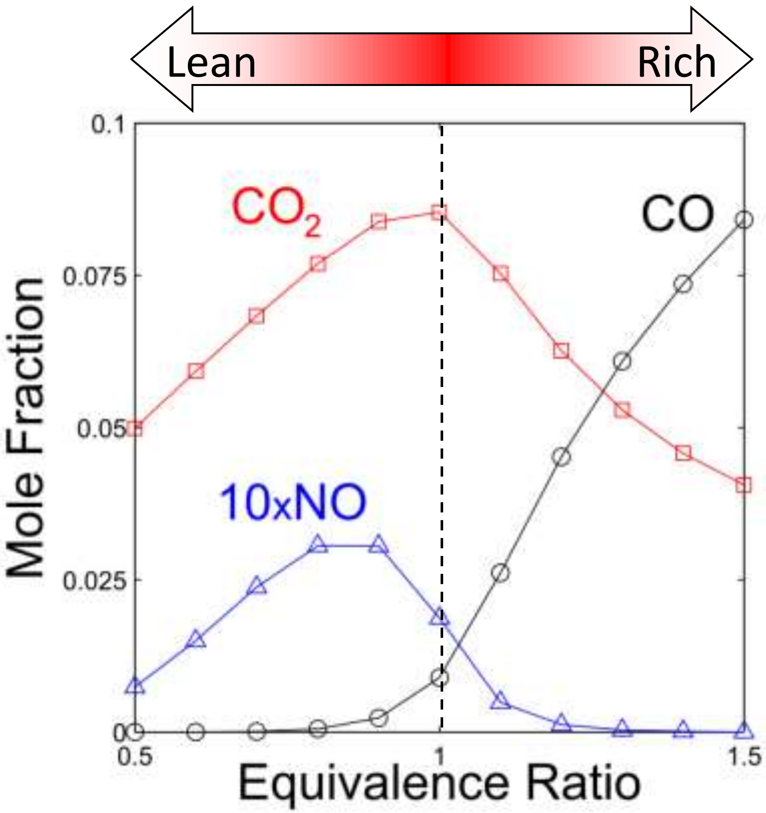
- Emissions (CO, NOx, CO_2, soot, etc)
- Limited resources of non-renewable combustibles (fossil fuel, coal, natural gas)
- Fuel economy independence

Technical solutions

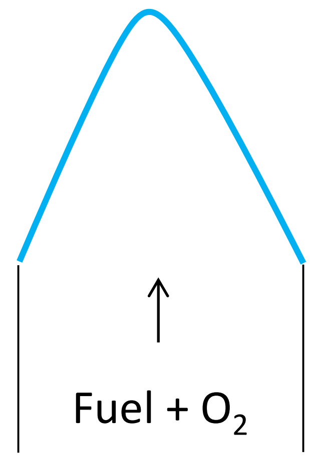
- Clean combustion technology
- Improved efficiency
- Alternative fuels and fuel-flexible devices

Strategy: Lean Premixed Combustion

Emissions of CO, CO_2 and NO in methane/air combustion (thermochemical equilibrium)



Premixed Combustion allows for control of the fuel/air ratio



Strategy: Lean Premixed Combustion

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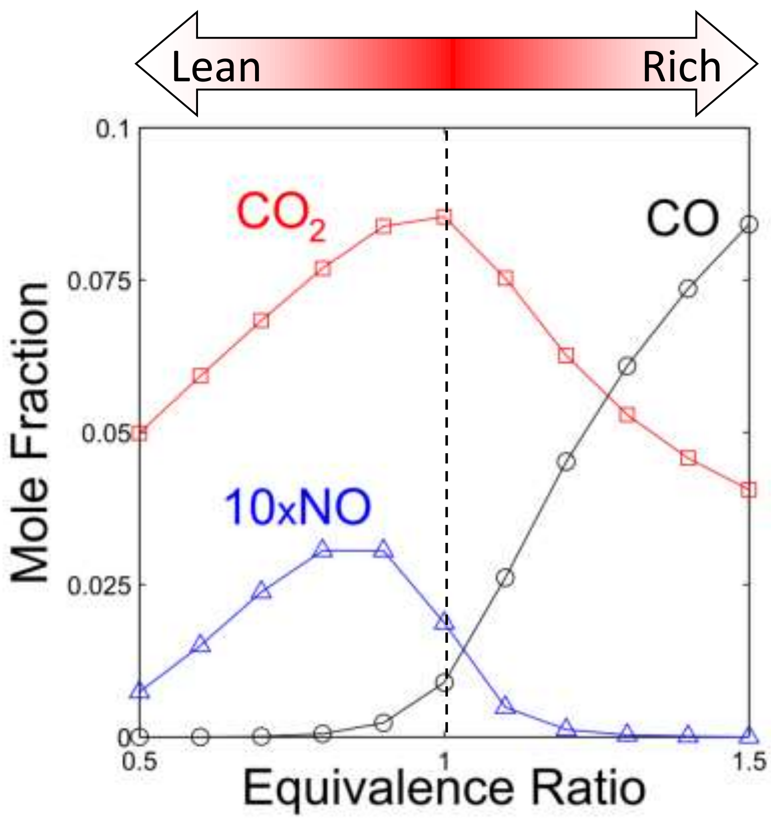
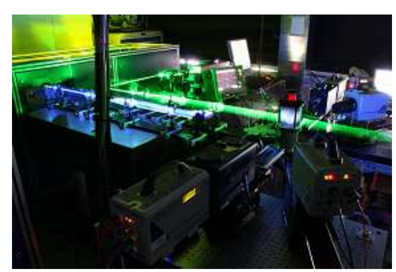


"The leaner, the cleaner"

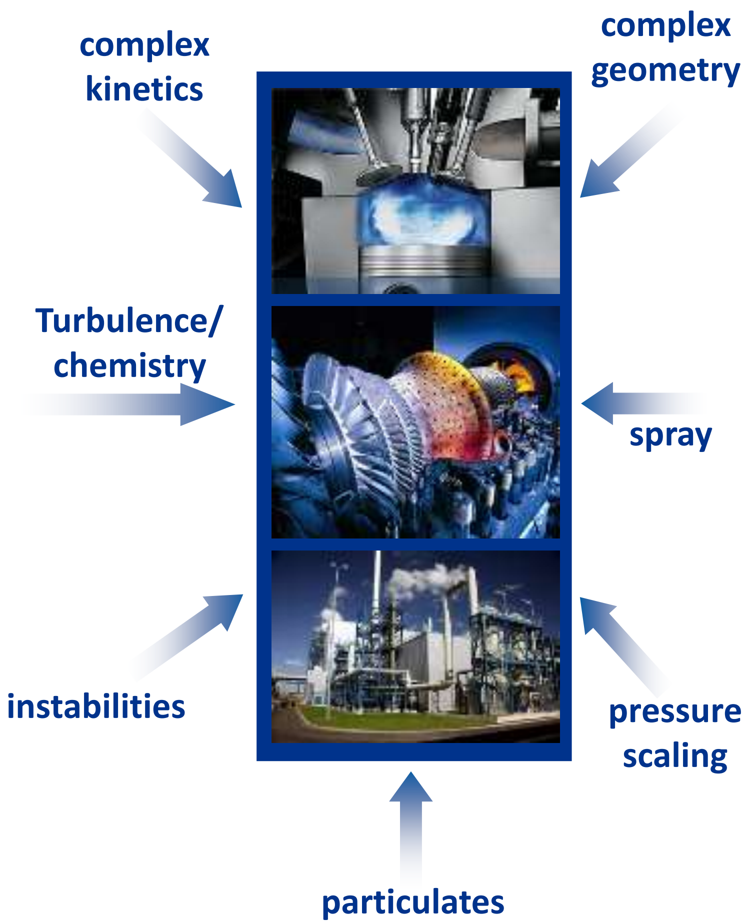
Fundamental Research Challenges

- Stability of lean premixed flames in intense turbulence.
- Pollutant emissions affected by the chemistry-turbulence interaction.
- Lean flames are sensitive to external perturbations (heat losses, dilution, strain, etc).
- Safety (flashbacks)

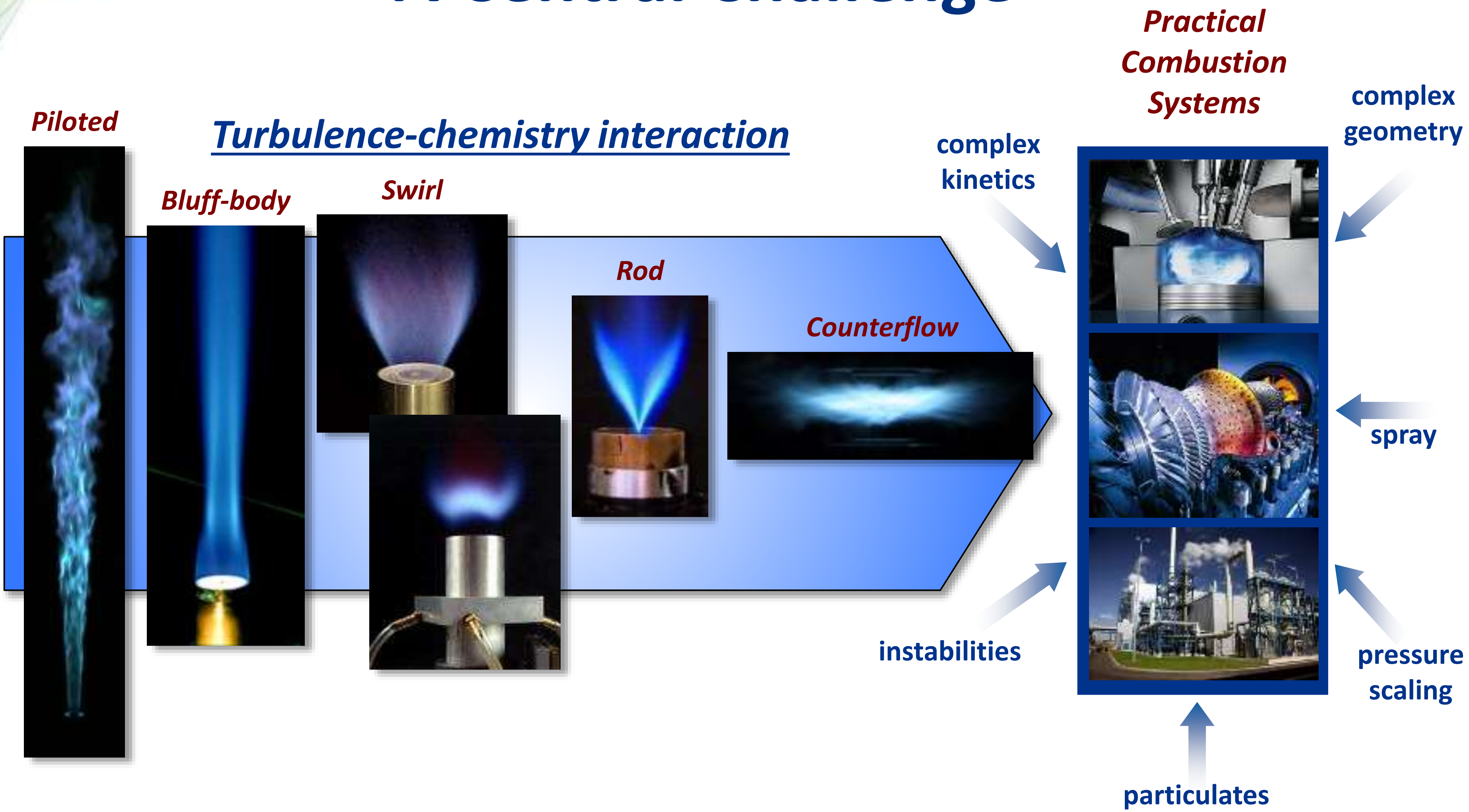


Fundamental Research Challenges

Practical Combustion Systems

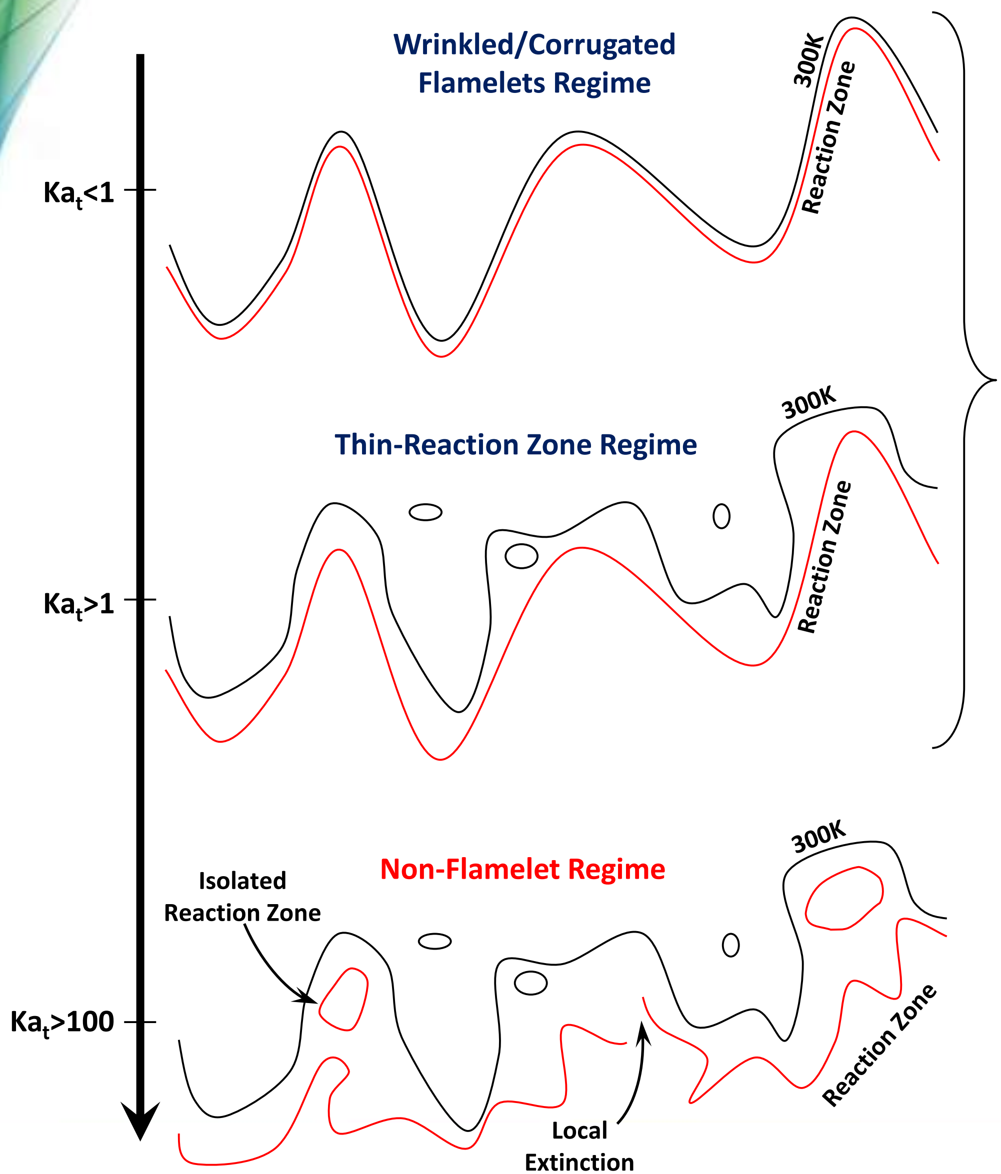


Turbulence-Chemistry Interaction: A Central Challenge



Well-characterized turbulent flames for canonical studies of turbulence – flame interactions

Turbulence-Chemistry Interaction: Theoretical Framework



Karlovitz number: $Ka_t = \frac{t_{chemical}}{t_{Kolmogorov}}$

Flamelet Regimes

- Quasi-laminar flame front structure
- Singly connected reaction zone

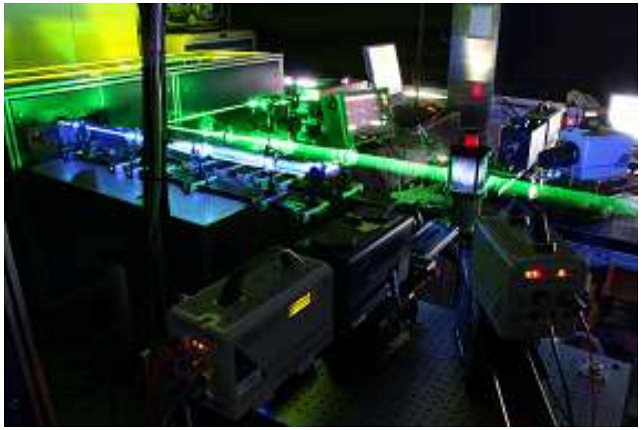
Non-Flamelet Regime

- Local Extinctions
- Distributed Reaction Zones
- Leakage of Reactants and Products across flame fronts

Laser Diagnostics for Turbulent Combustion Studies

Laser diagnostics are a non-intrusive means of measuring a wide range of quantities, such as:

- **Velocity vectors** – Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV)
- **Intermediate species (OH, CH_2O, CO, etc) and forward reaction rates** – Laser Induced Fluorescence (LIF), Raman scattering, Soft X-Ray absorption.
- **Temperature** – Rayleigh Scattering
- **Scalar Mixing and Mixture fraction** – LIF imaging of "tracers" (Kr, Acetone, etc)



Features of laser diagnostics in combustion:

- Multiple simultaneous measurements
- Probe domain: point, line, plane or volume
- Spatial resolution: 10μm – to – 100μm
- Temporal resolution: 10ns – to – 100ns, ~10μs for PIV
- Data acquisition rate: 1Hz – to – 10kHz

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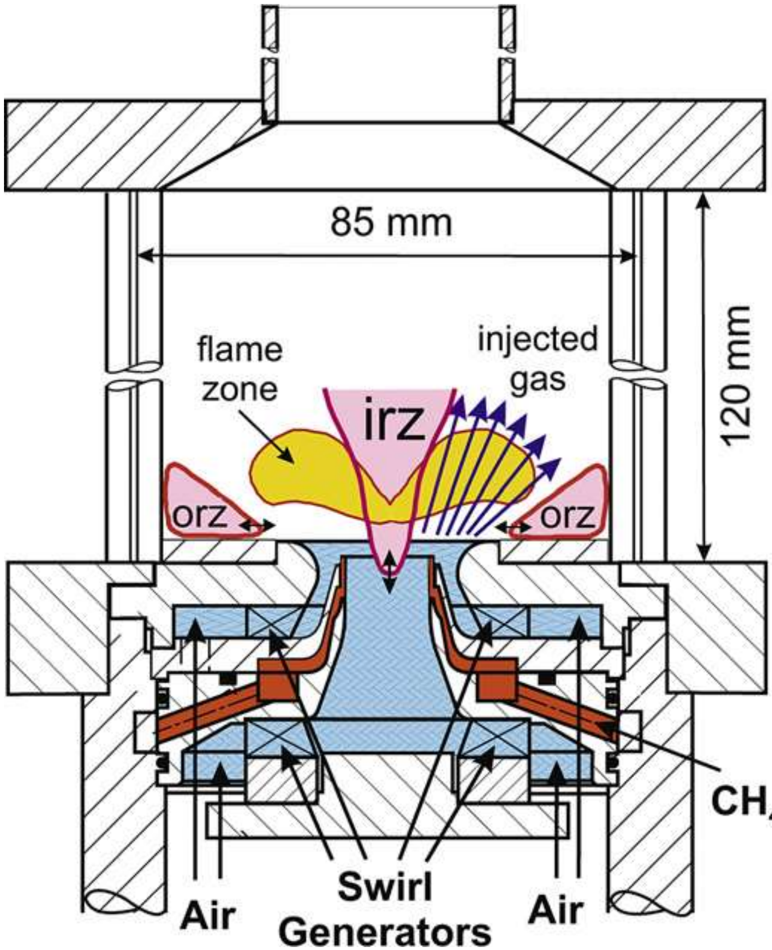
Motivations

DLR Swirl Stratified Combustor
(Kutne *et al.*, 2010)

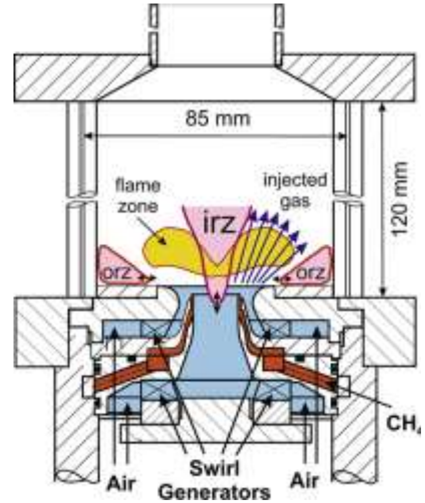


Practical turbulent flames are exposed to external perturbations such as

- heat loss/gain,
- dilution by hot products,
- large bulk strain rate,
- Reactant stratification…

Motivations

Turbulent flame stabilization often involves the mixing of reactants with products of combustion.



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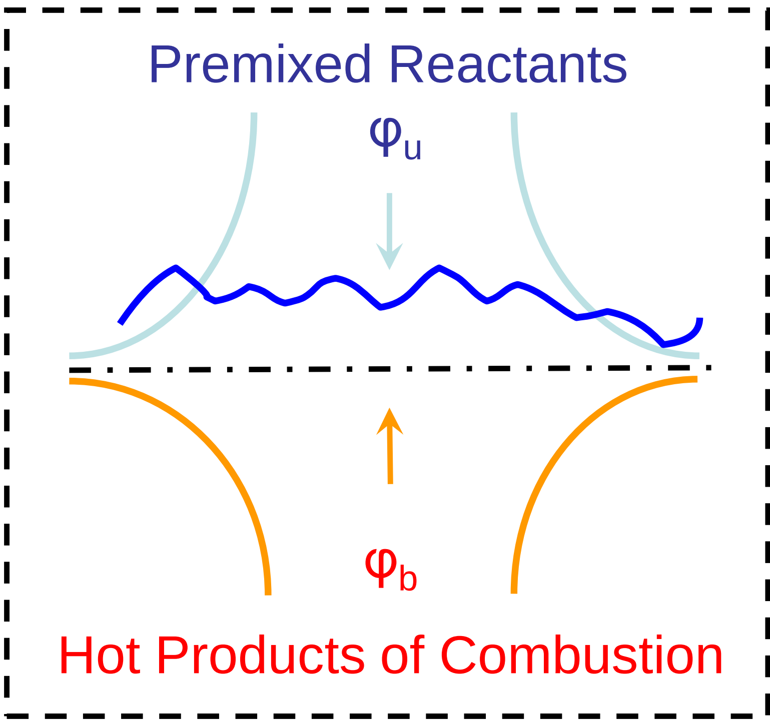
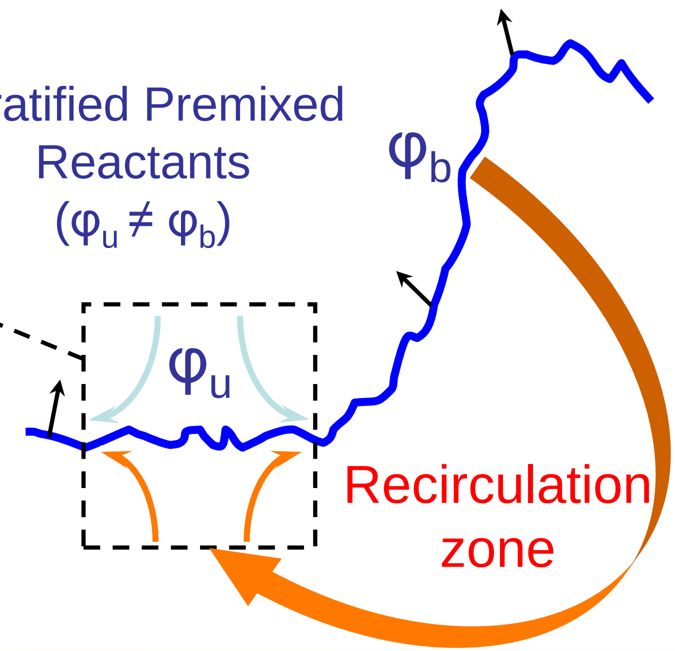
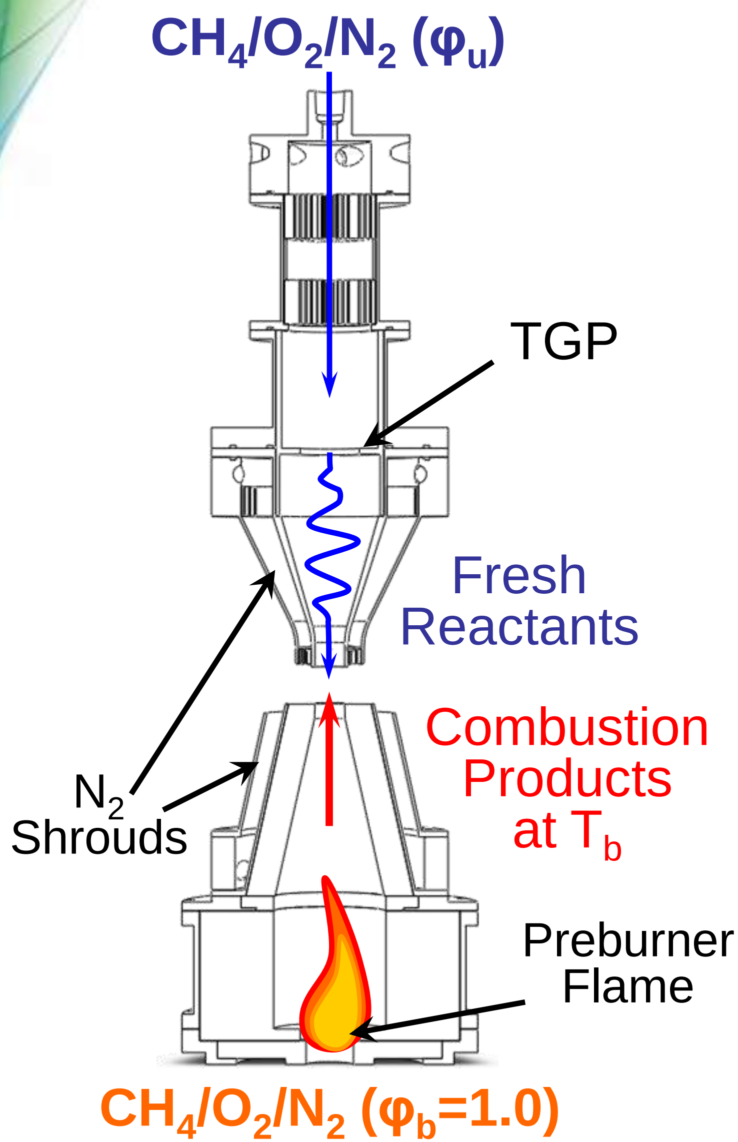




Turbulent Counterflow Burner



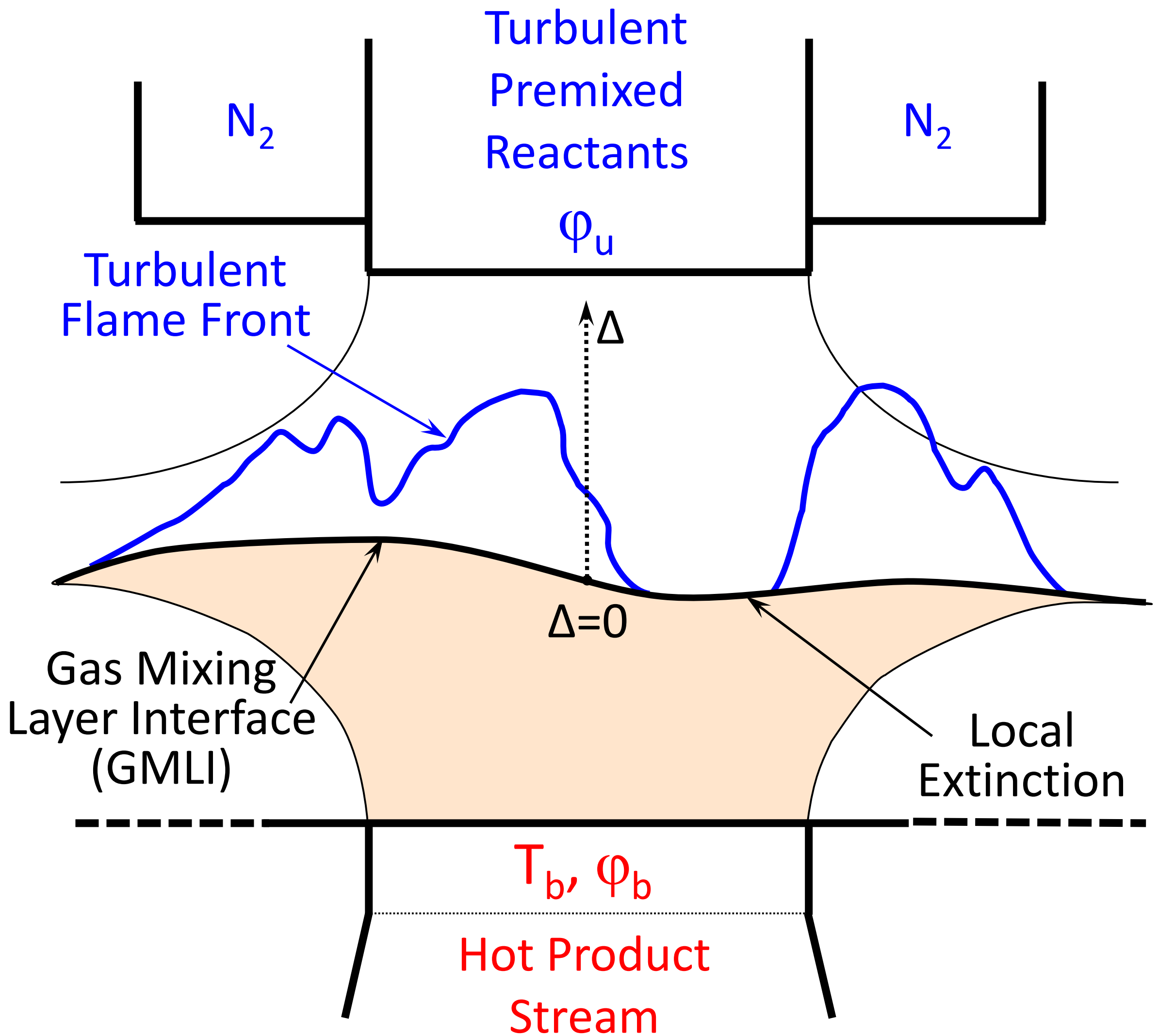
Large range of flow conditions:

- Bulk Strain Rate, $K_{bulk} = 2U_u/d_{nozzle}$
- Turbulent Reynolds Number, $Re_t = u'l'/\nu$
- Non-adiabaticity, $T_b \neq T_{ad}$
- Stratification, $\varphi_u \neq \varphi_b$

K_{bulk}	1400/s – 2240/s
Re_t	470 - 1050
T_b	1500K – 2000K (1850K)
φ_u	lean (0.7) to rich (1.2)
φ_b	lean (0.7) to rich (1.2)

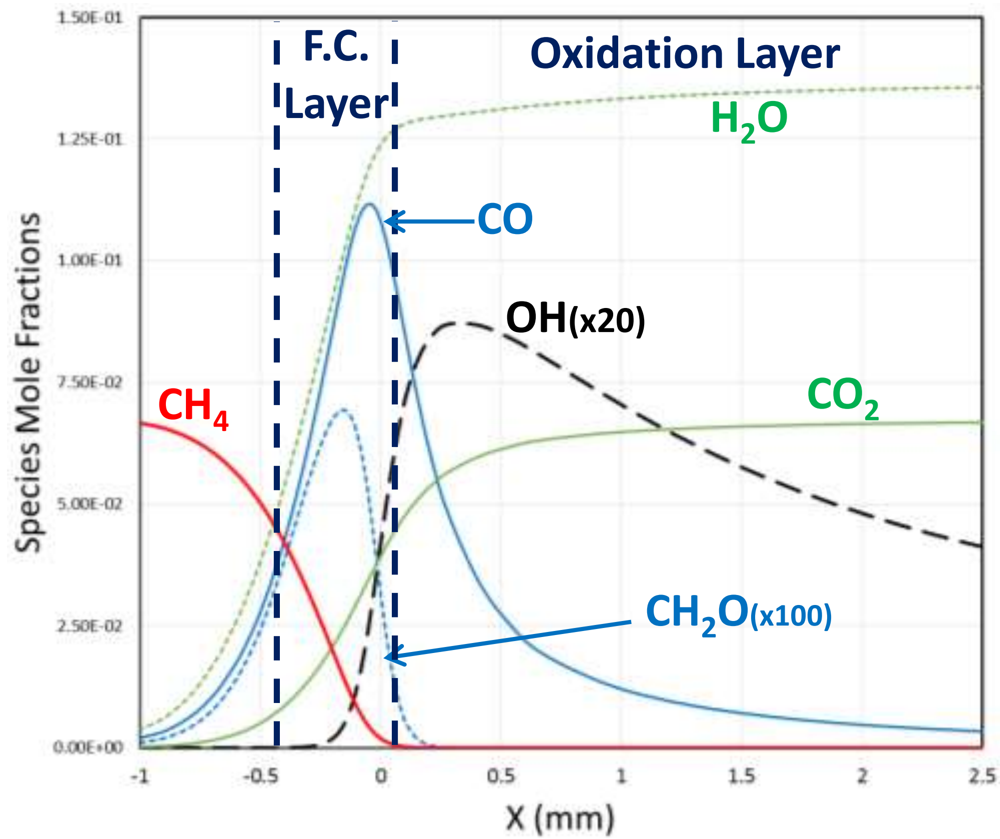
$$Ka_t = \frac{t_{ch}}{t_\eta} = \left(\frac{v'}{S_L}\right)^{3/2}\left(\frac{l_F}{l'}\right)^{1/2} = O(1\text{-}10)$$

Turbulent Flame Phenomenology



Laminar Premixed Flame Structure

Flame chemistry involves many species and chemical reactions.



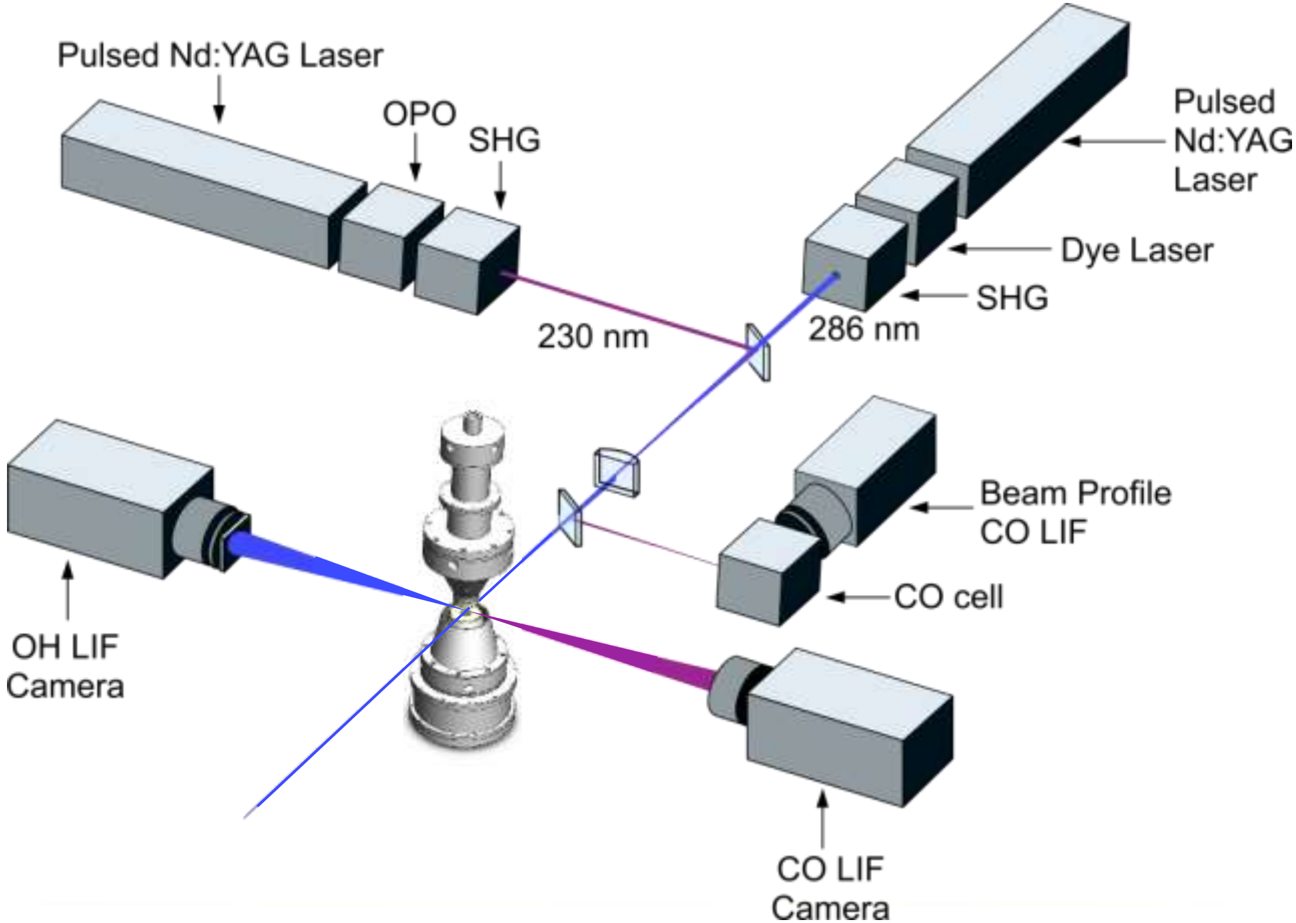
Two reaction-zone regions:

- Fuel-consumption layer: CH2O + OH → H2O + HCO correlates with peak of heat release rate (Najm *et al.*, 1998).
- CO oxidation layer: CO + OH → CO_2 + H dominant pathway for CO oxidation

Laser diagnostics are the only way to measure reaction rates in turbulent flames.

Reaction Rate Imaging
$CO + OH \rightarrow CO_2 + H$

Simultaneous recording of single-photon OH-LIF and two-photon CO-LIF.



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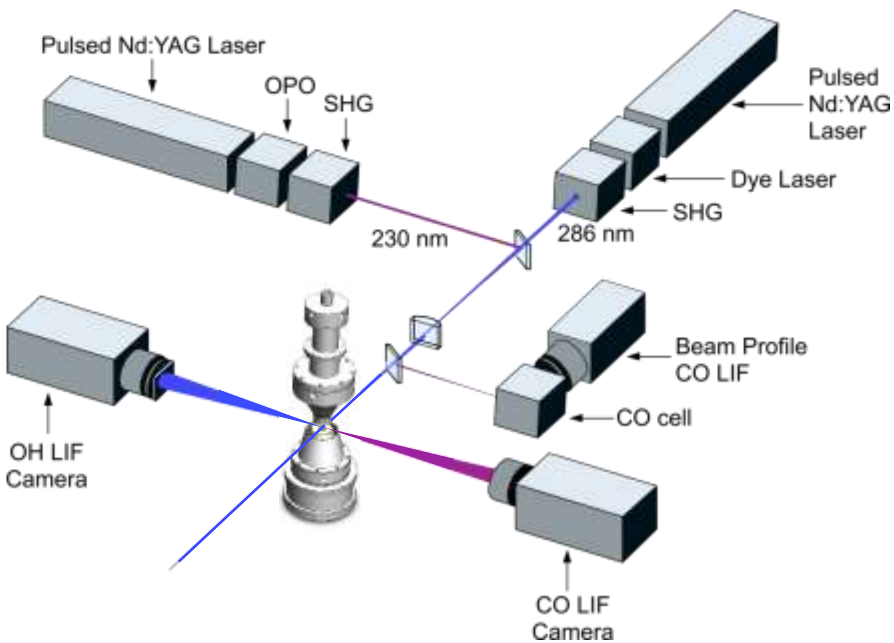


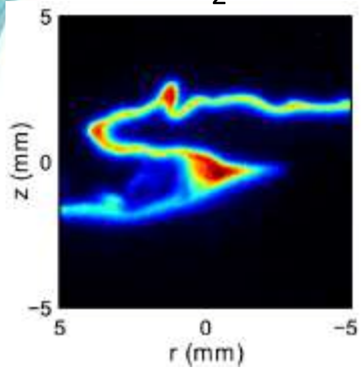
- Simultaneous recording of single-photon OH-LIF and two-photon CO-LIF.
- In combination, OH-LIF and CO-LIF signals yield a quantity proportional to the forward reaction rate (RR) for $CO + OH \rightarrow CO_2 + H$.

$$RR = k(T)[CO][OH]$$
$$\propto f_{CO}(T)f_{OH}(T)[CO][OH]$$

- f_{CO} and f_{OH} account for the temperature dependence of the CO-LIF and OH-LIF signals, respectively.
- $f_{CO}(T)f_{OH}(T)$ proportionality to $k(T)$ is estimated with a deviation of ±5% for the premixed flames studied.

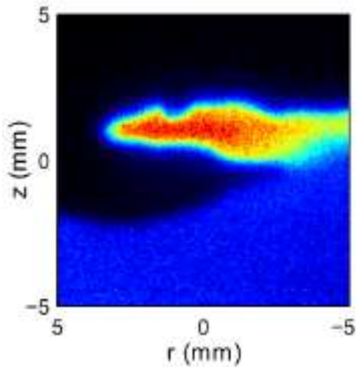
Reaction Rate Imaging

CO/CH_2O LIF

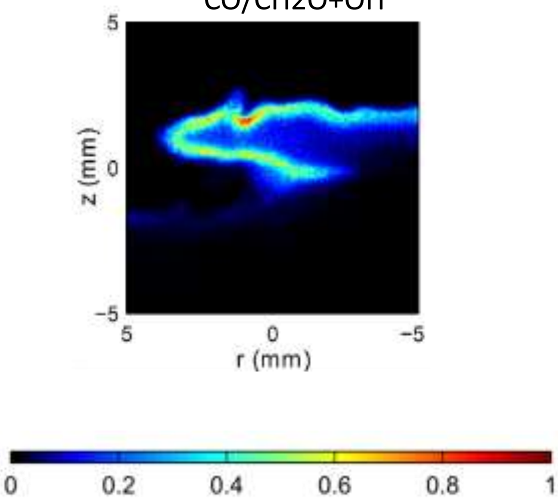


X

OH LIF



$RR_{CO/CH2O+OH}$



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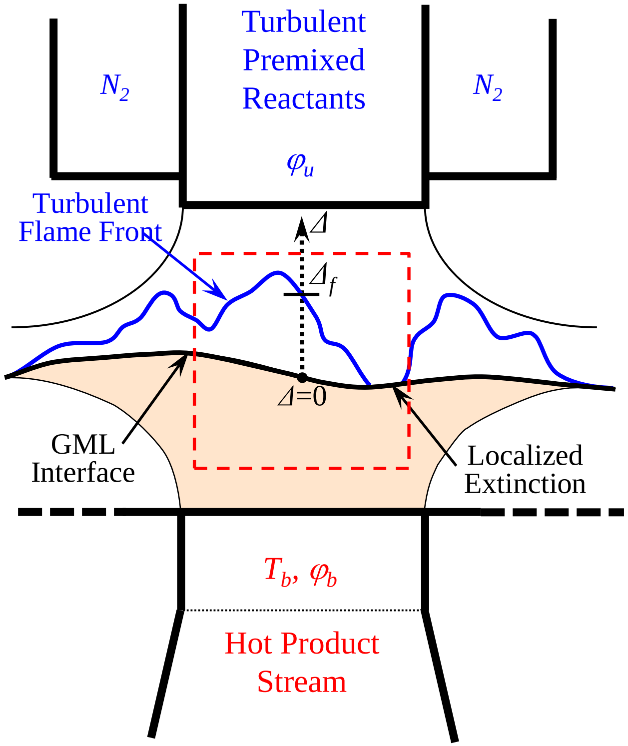
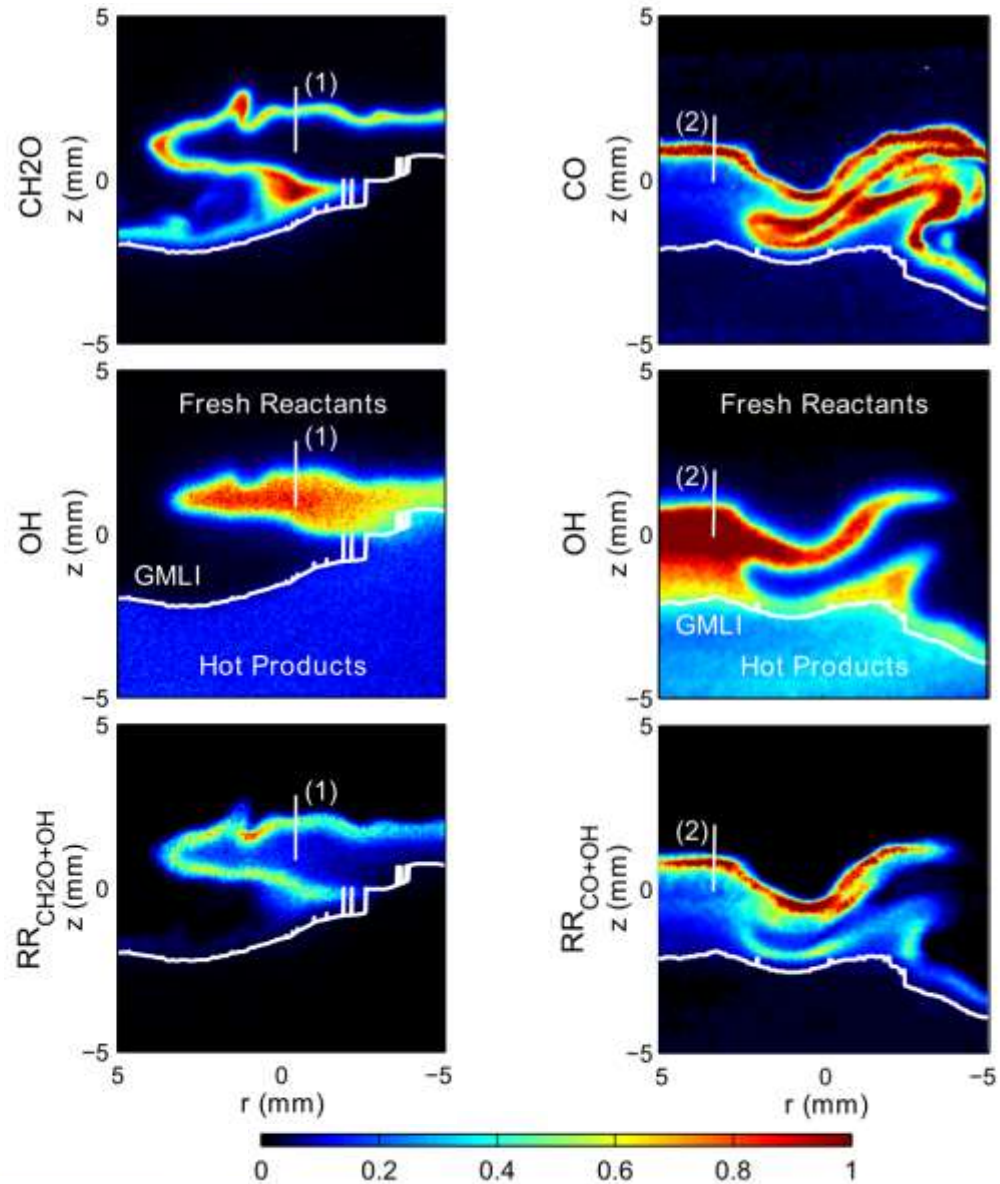
Turbulent Flame Front Structure





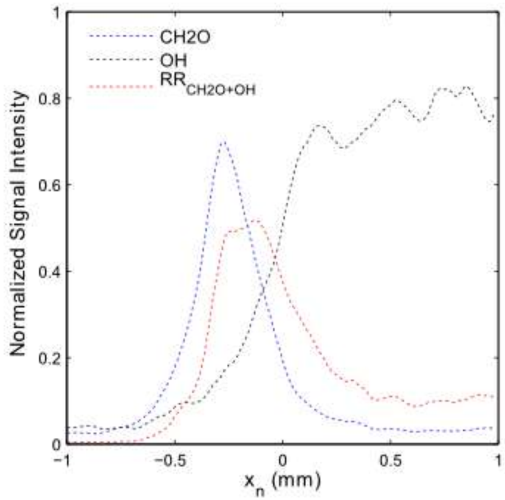
Flow Conditions:

- K_{bulk} = 1400/s
- Re_t = 1050
- φ_u = 0.8
- T_b = 1850K

Turbulent Flame Front Structure

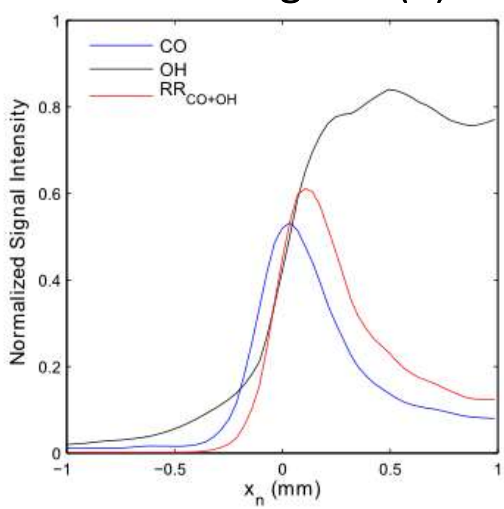
$CH_2O + OH \rightarrow H_2O + HCO$

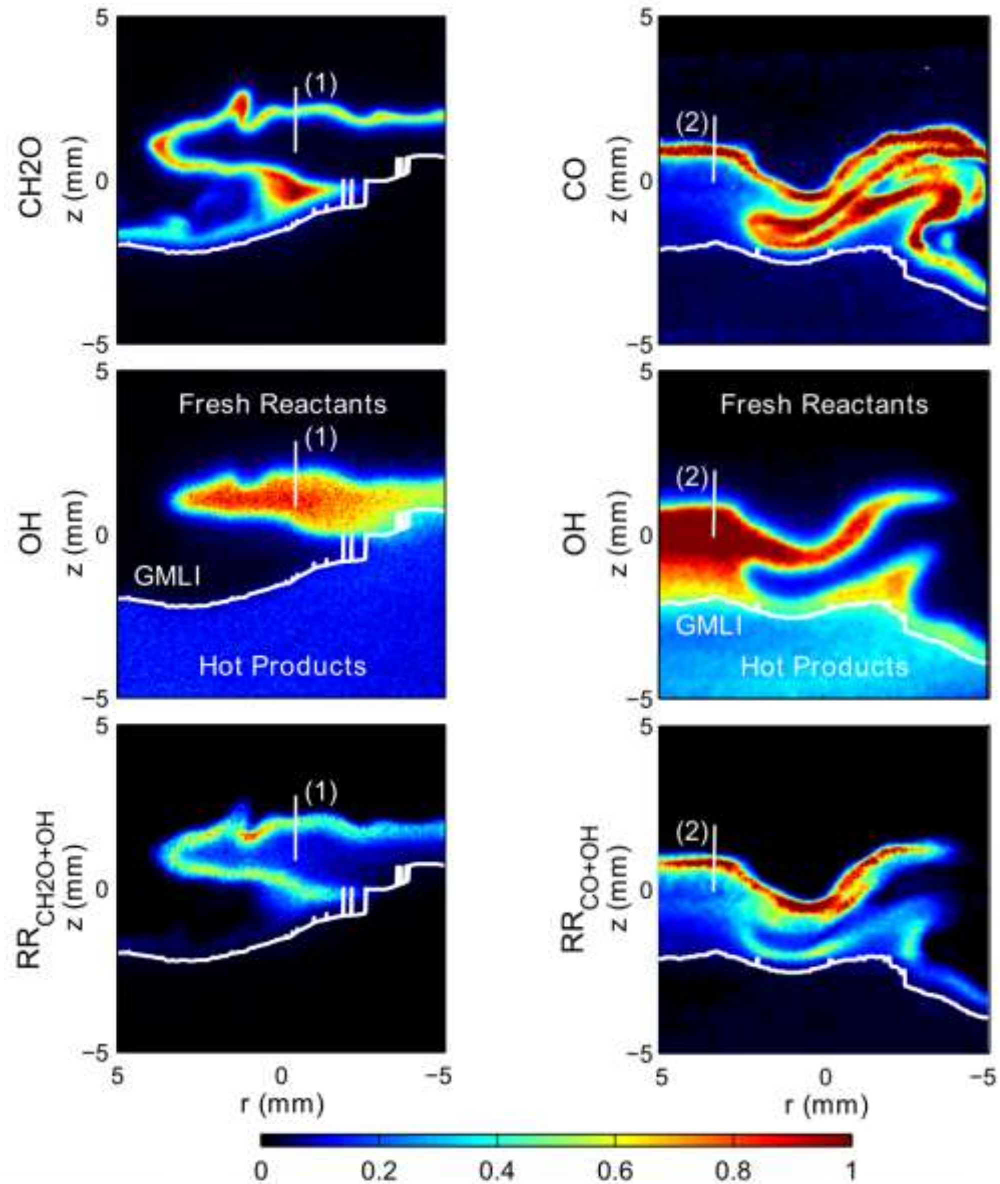
Plot along line (1)



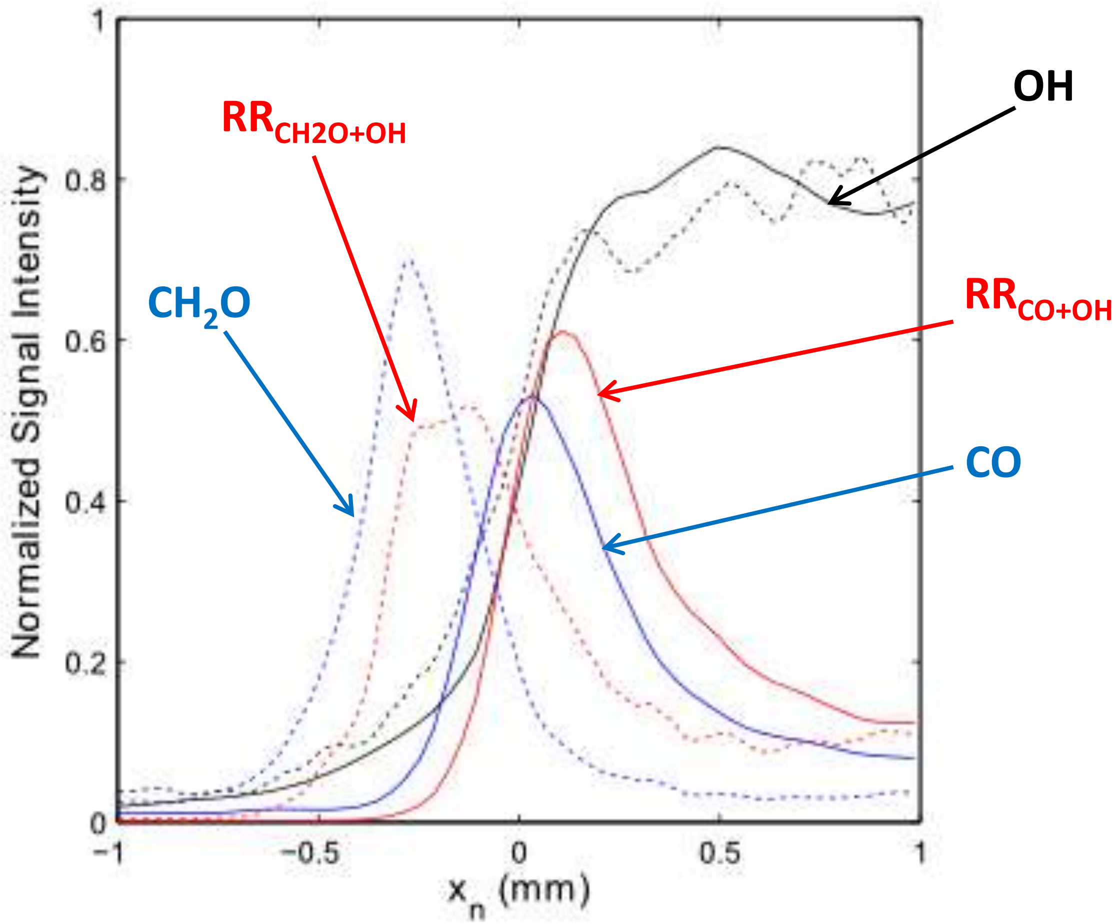
$CO + OH \rightarrow CO_2 + H$

Plot along line (2)



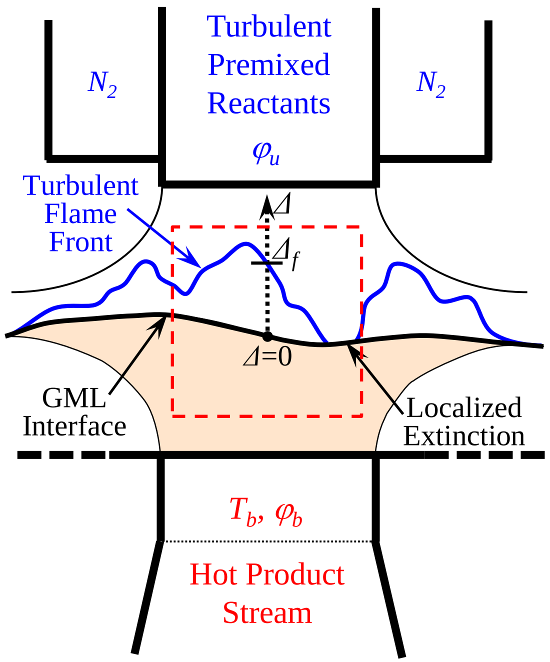


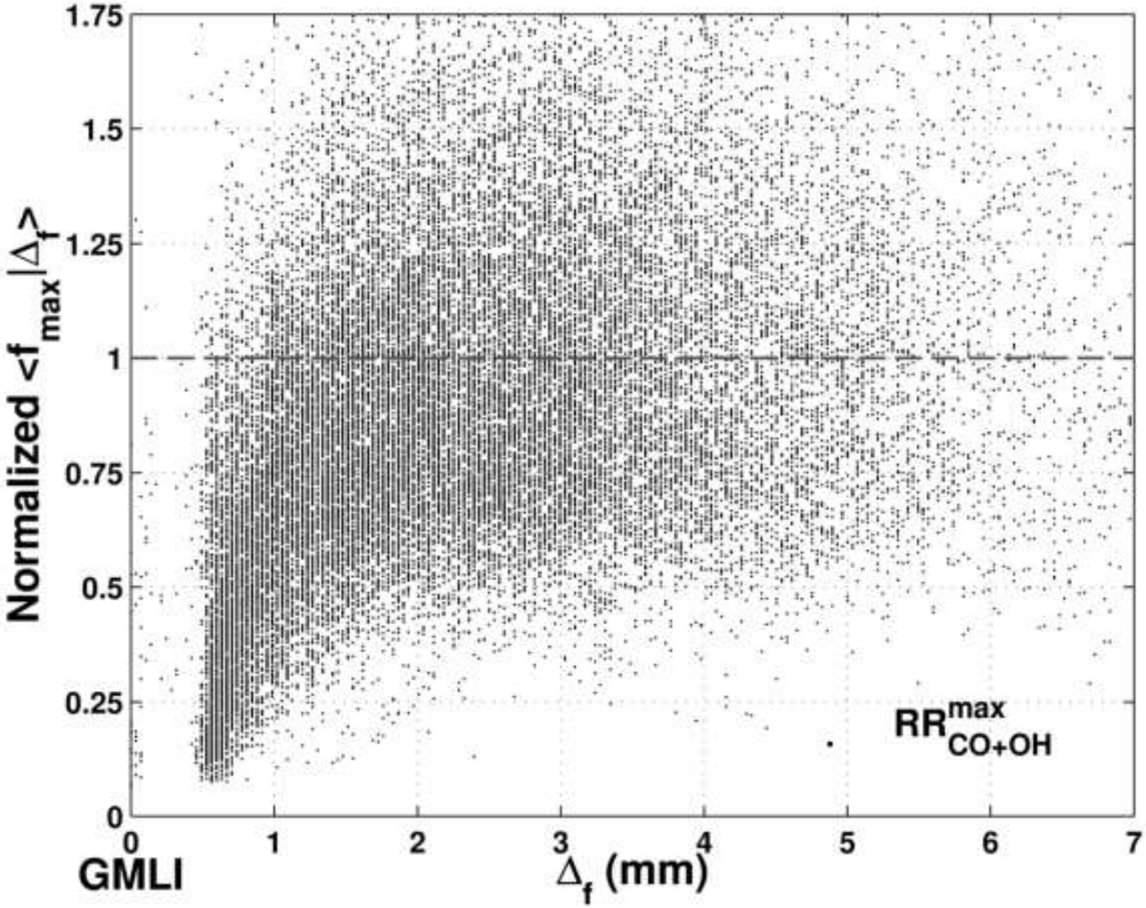
Turbulent Flame Front Structure



- Turbulent flame structure is flamelet-like.
- We are going to monitor RR_{max} as a function of Δ_f (distance from GMLI).

Effect of combustion products on $CO + OH \rightarrow CO_2 + H$

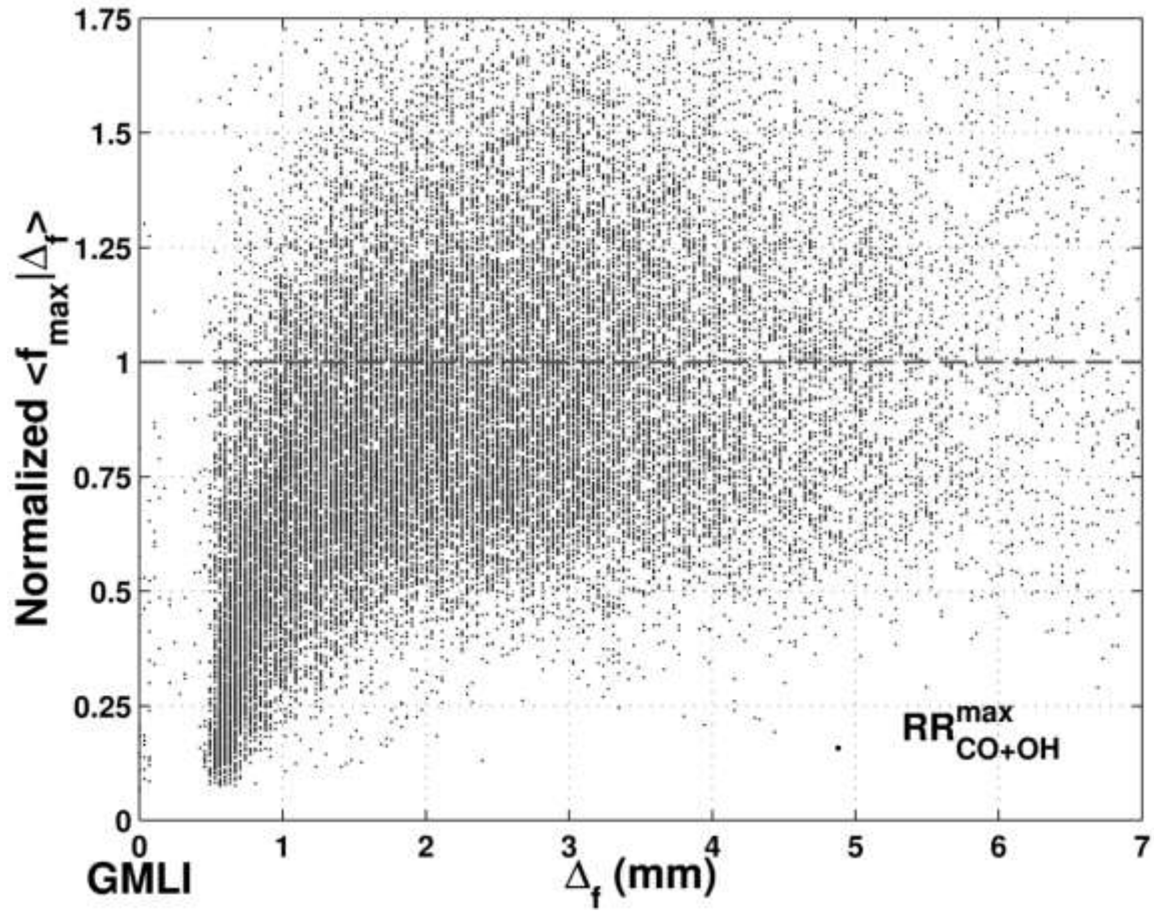




Scatter plot of Peak RR_{CO+OH}

Effect of combustion products on $CO + OH \rightarrow CO_2 + H$

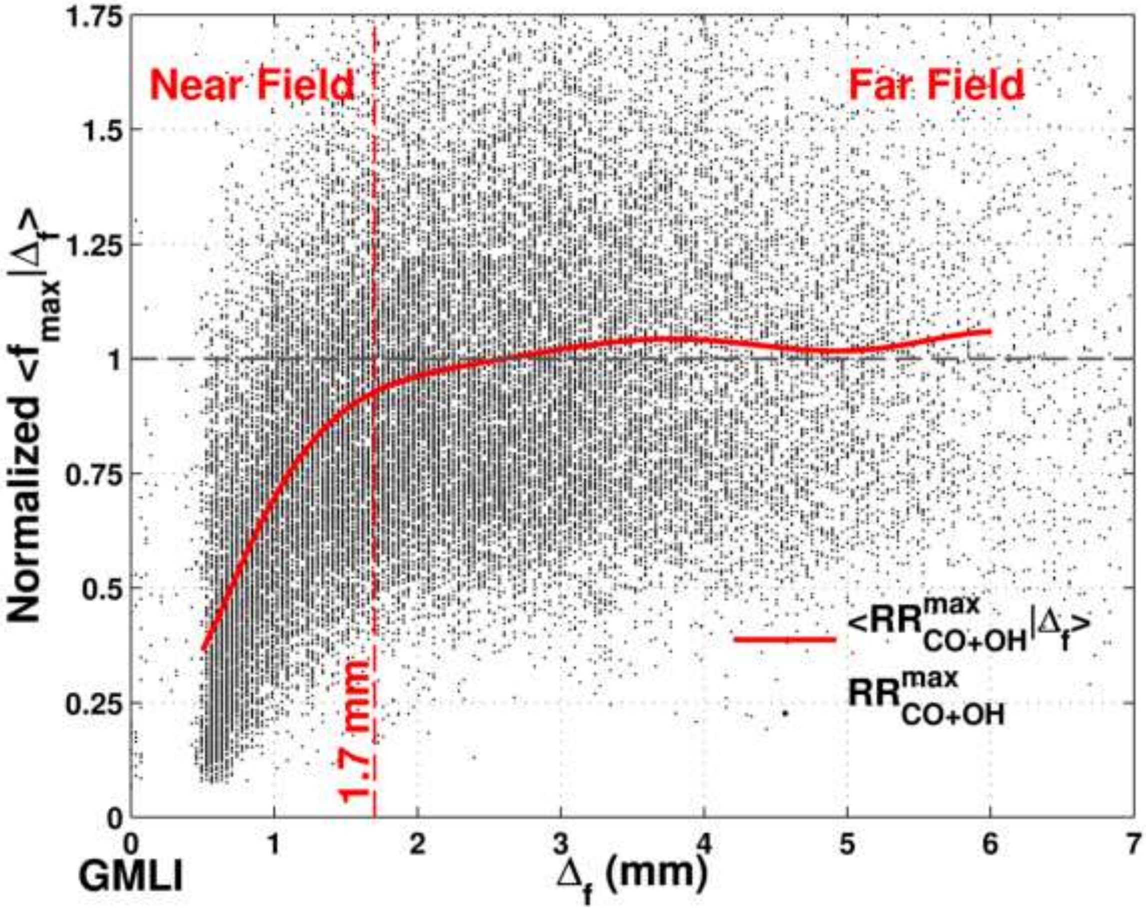
- RR_{max} scattering is due to turbulence – chemistry interaction.



Scatter plot of Peak RR_{CO+OH}

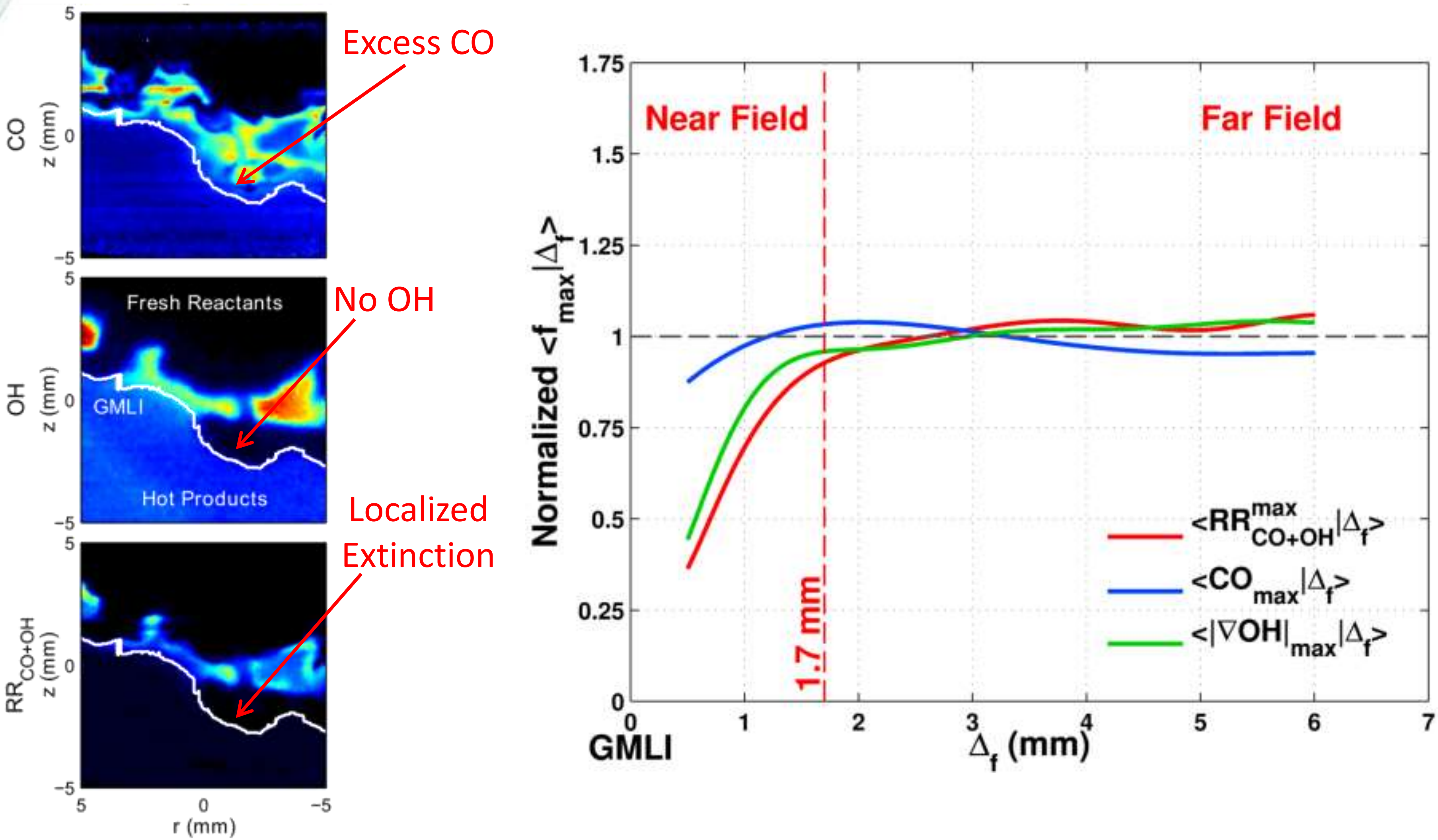
Effect of combustion products on $CO + OH \rightarrow CO_2 + H$

- RR_{max} scattering is due to turbulence – chemistry interaction.
- Two regions:
  - Near-field (Δ_f < 1.7mm)
  - Far-field (Δ_f > 1.7mm).
- Attenuation of burning rate in the near field.
- RR_{max} is unaffected by counterflowing products in the far-field.



Scatter plot of Peak RR_{CO+OH}

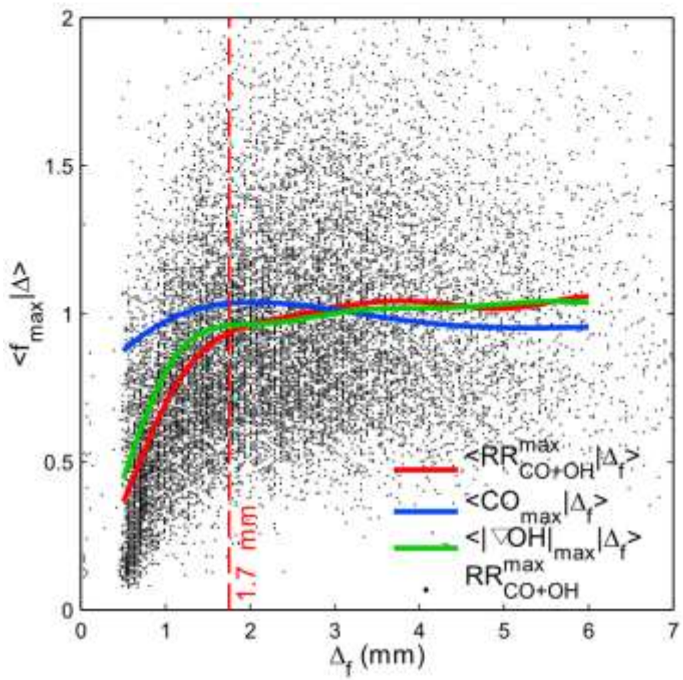
Flame structure properties in Near Field and Far Field



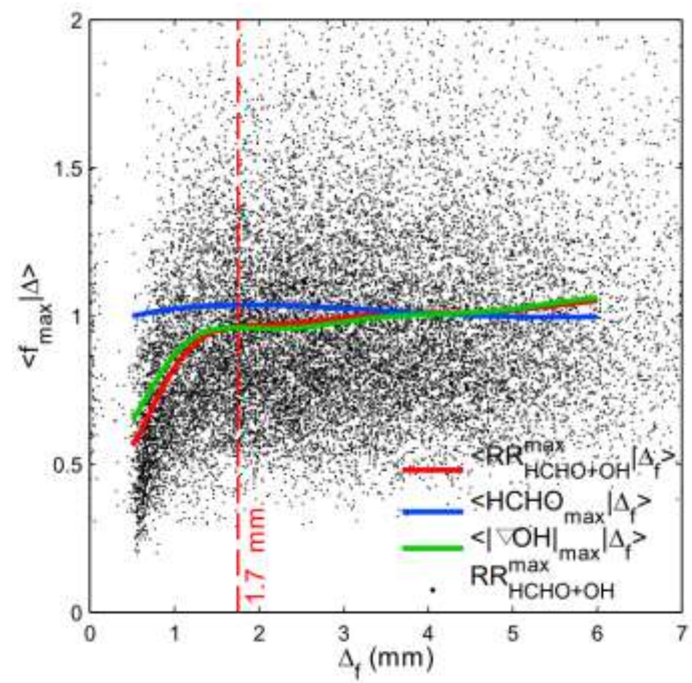
Decrease in reaction rates correlates with depletion of OH radicals in the vicinity of the GMLI.

Same results in Fuel Consumption Layer and CO oxidation Layer

$CO + OH \rightarrow CO_2 + H$



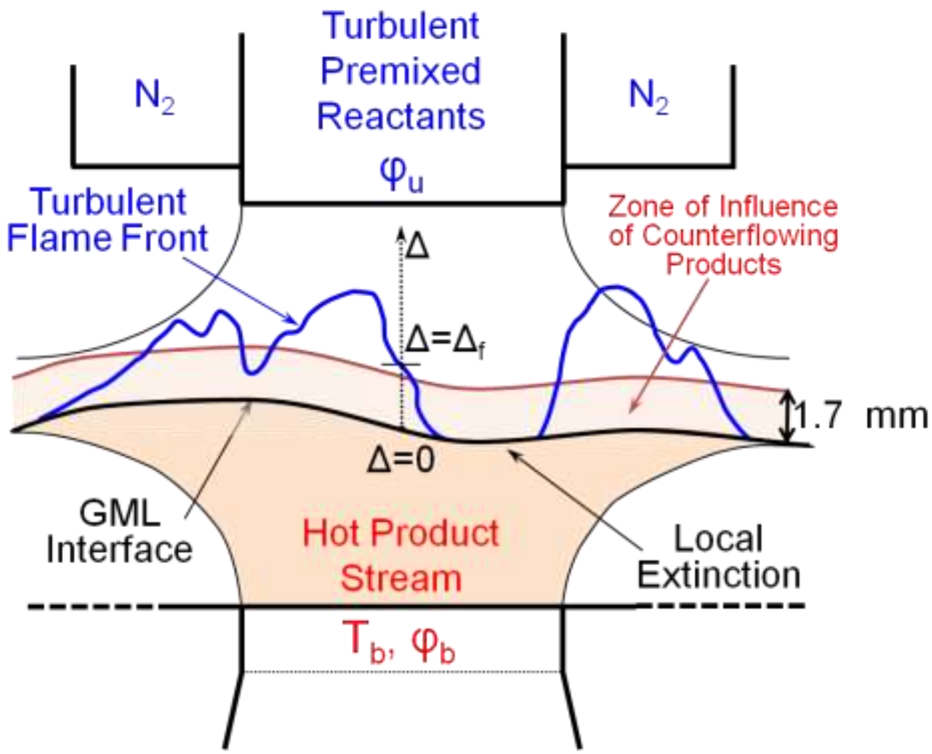
$CH_2O + OH \rightarrow H_2O + HCO$



- Depletion of OH radicals near the GMLI is responsible for RR attenuation.
- Both CO and CH_2O species remain produced by fuel pyrolysis/oxidation.

Part II – Summary

- Significant RR attenuation and localized extinctions occur along the GMLI.
- No extinction outside the zone of influence of counterflowing products.
- Zone of influence of combustion products: ~1.7 mm.
- Depletion of OH correlates with extinction
- OH LIF signal can be used as a marker of localized extinctions in these flames.



Part II – Impact

Peer-reviewed publications:

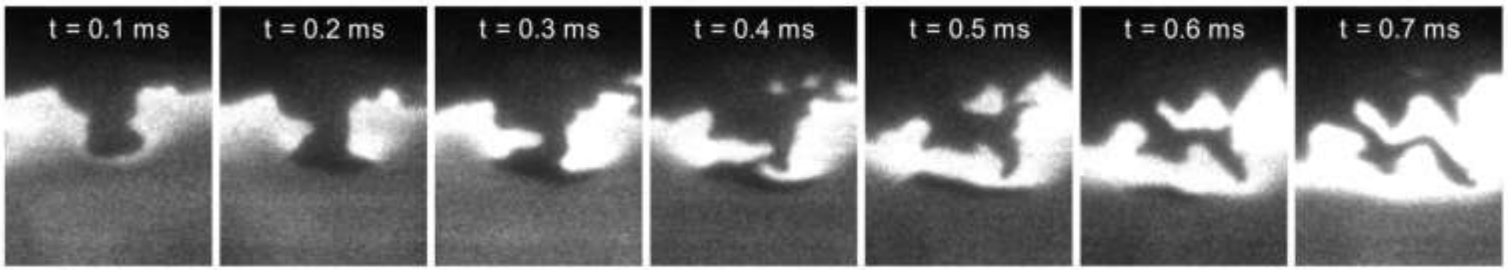
- **B. Coriton**, J.H. Frank, A. Gomez, Combust. Flame (2016), *in press*.
- **B. Coriton**, J.H. Frank, A. Gomez, Combust. Flame 160 (2013) 2442-2456.
- **B. Coriton**, J.H. Frank, A.G. Hsu, M.D. Smooke, A. Gomez, Proc. Combust. Inst. 33 (2010) 1647-1654.
- M.W.A. Pettit, **B. Coriton**, A. Gomez, A.M. Kempf, Proc. Combust. Inst. 33 (2010) 1391-1399.
- **B. Coriton**, M.D. Smooke, A. Gomez, Combust. Flame 157 (2010) 2155-2164.
- G. Coppola, **B. Coriton**, A. Gomez, Combust. Flame 156 (2009) 1834-1843.

Collaborations with modeling groups:

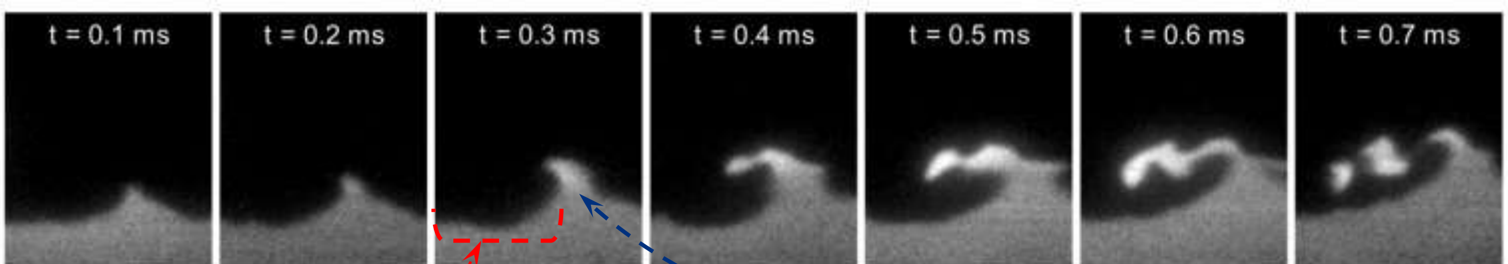
- Joe Oefelein, Jackie H. Chen (Sandia National Labs)
- Steve B. Pope (Cornell University)
- Andreas M. Kempf (Univ. of Duisburg-Essen)
- CRAFT Tech - Combustion Research and Flow Technology, Inc.
- “Target burner” – TNF workshops

Dynamics of flame extinction/re-ignition
- High Speed OH-LIF Image Sequence -

Flame edge propagation (φ_u=1.0)



Localized Ignition (φ_u=0.5)



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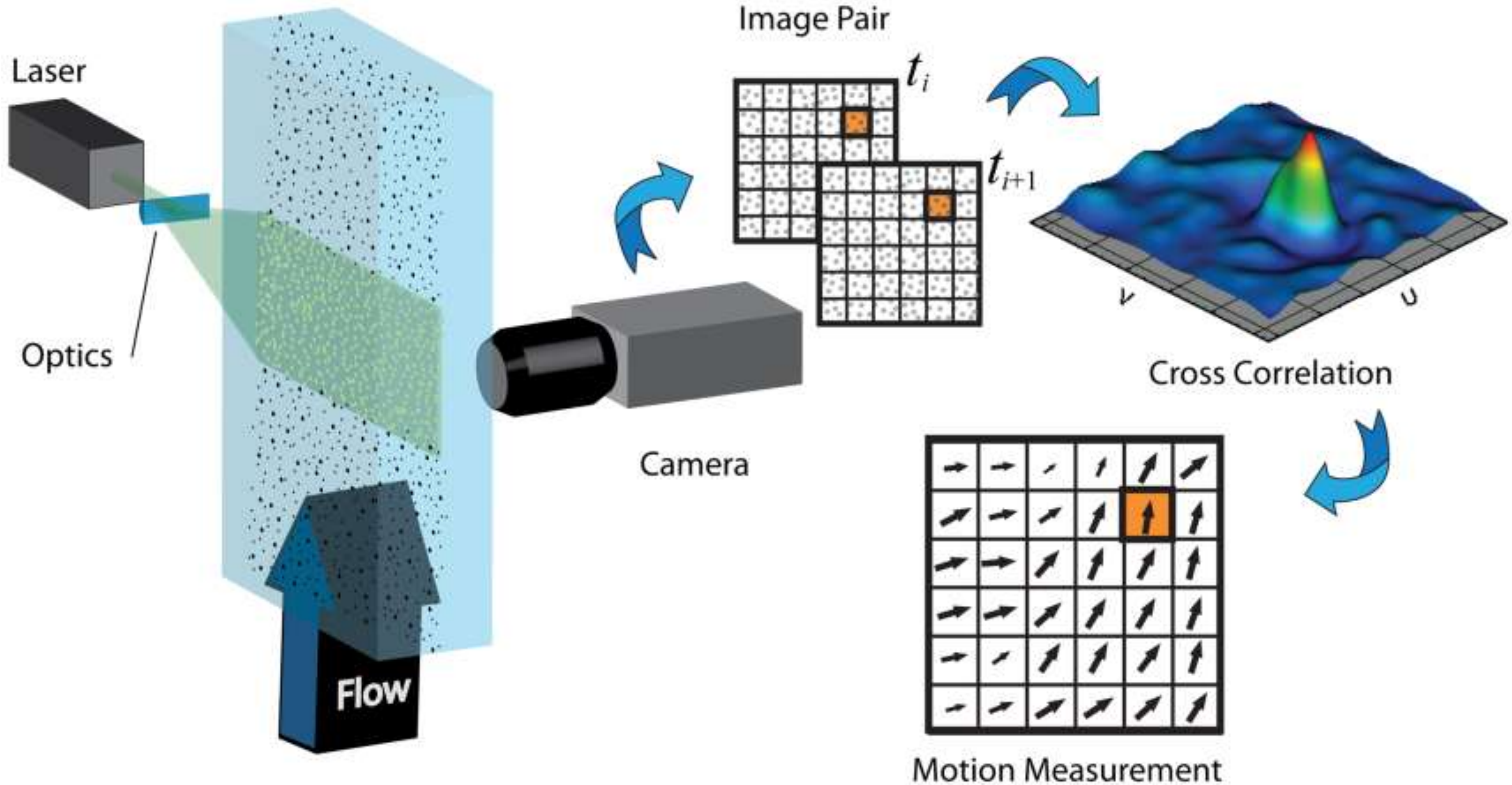
Velocity Gradient Tensor

$$\nabla v = \begin{bmatrix} \partial u/\partial x & \partial u/\partial y & \partial u/\partial z \\ \partial v/\partial x & \partial v/\partial y & \partial v/\partial z \\ \partial w/\partial x & \partial w/\partial y & \partial w/\partial z \end{bmatrix} = \frac{1}{3}\Delta I_3 + \Omega + S$$

- **Divergence:** $\Delta = \nabla . v$ *(unavailable in 2D)*
- **Rate of Rotation:** $\Omega = \frac{1}{2}(\nabla v - \nabla v^T)$ *(biased in 2D)*
- **Vorticity:** $\omega = \nabla \times v$ *(only out-of-plane component in 2D)*
- **Rate of Strain:** $S = \frac{1}{2}(\nabla v + \nabla v^T)$ *(biased in 2D)*

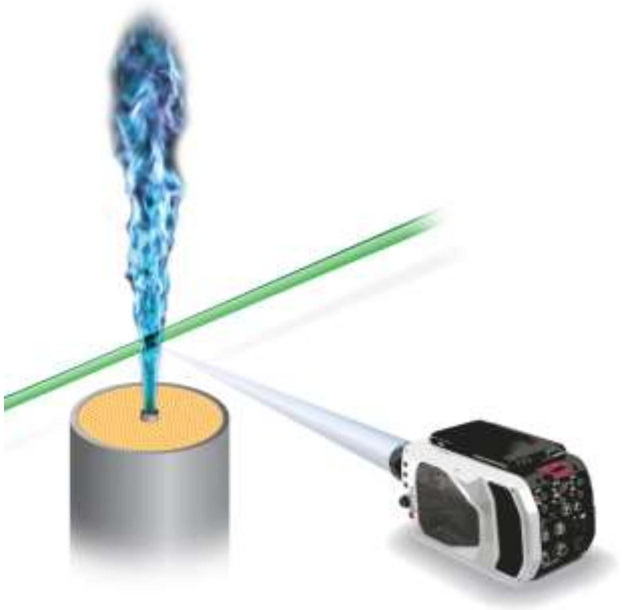
Particle Image Velocimetry (PIV) Principle



Particle Image Velocimetry Configurations

Planar PIV
2 velocity components in 2-D

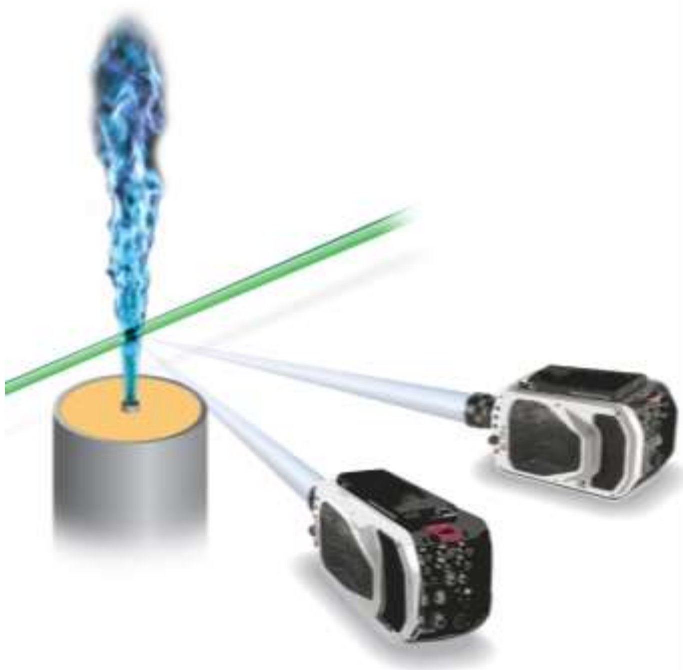
$$v = u\hat{i} + v\hat{j} + w\hat{k}$$



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

Particle Image Velocimetry Configurations

Stereoscopic PIV
3 velocity components in 2-D



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

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

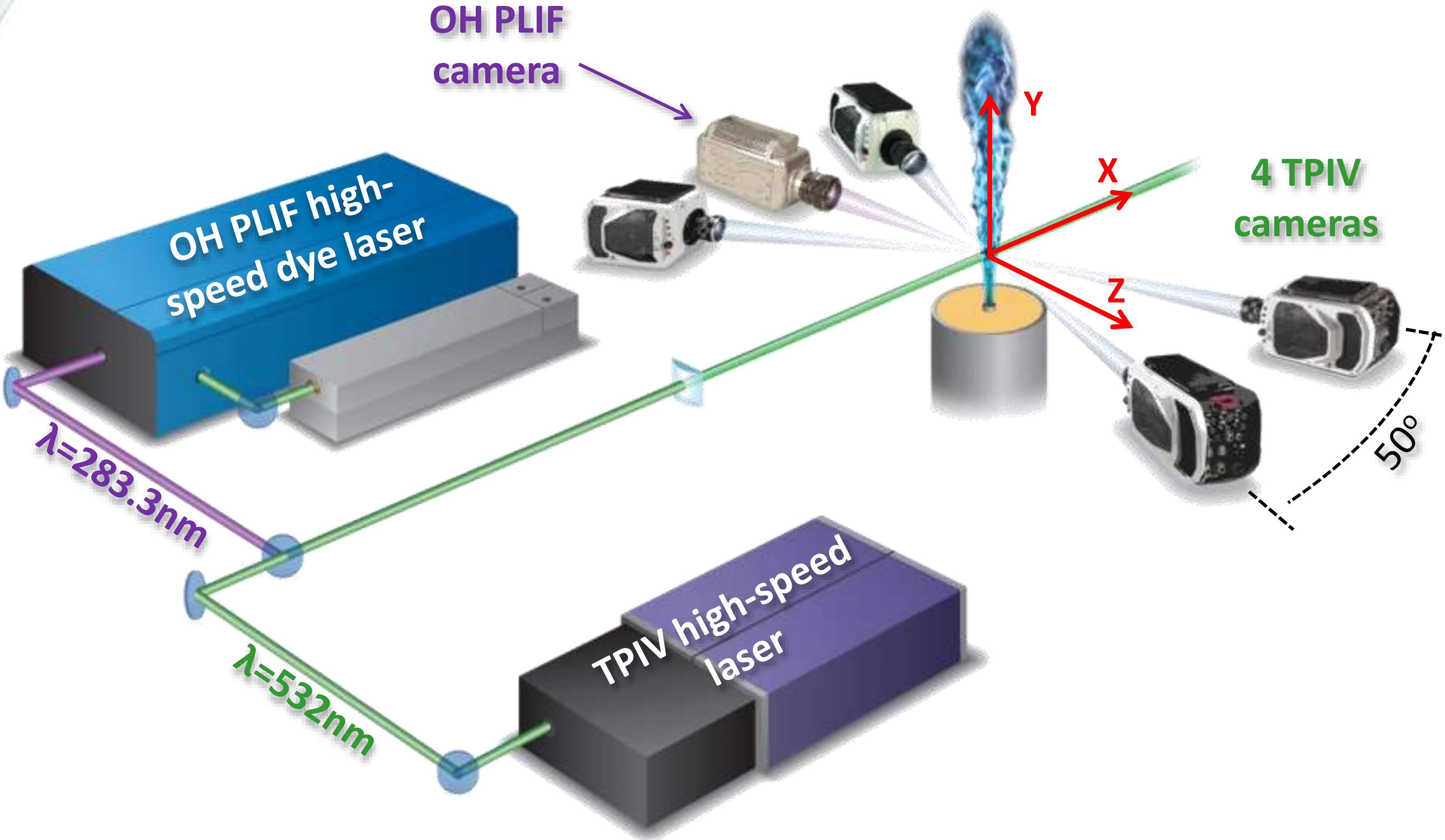
Particle Image Velocimetry Configurations

Tomographic PIV
3 velocity components in 3-D

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

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

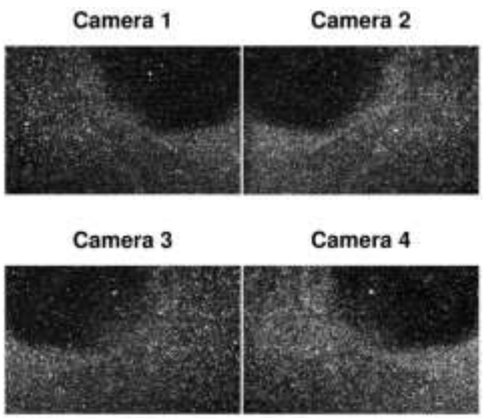
Experimental Apparatus



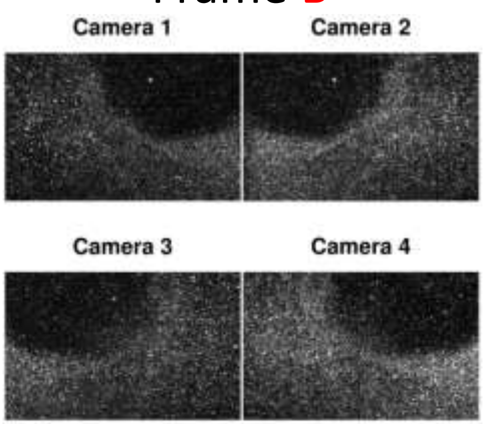
Principle of Tomographic PIV

Data Acquisition

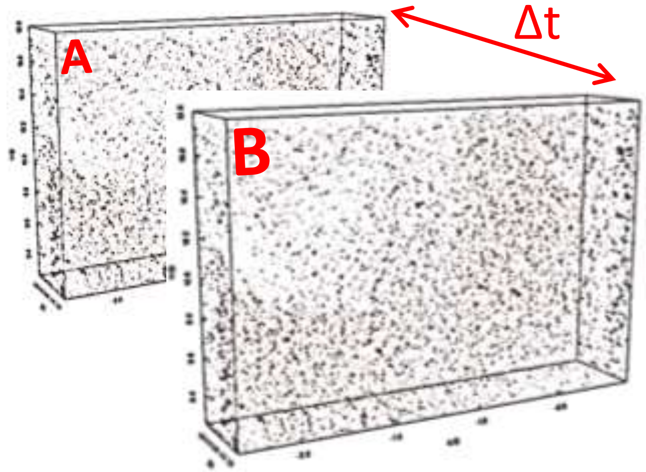
Frame A



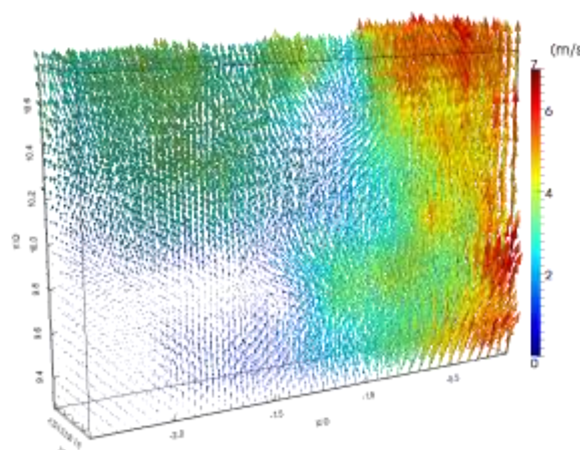
Frame B



Probe Volume Reconstruction

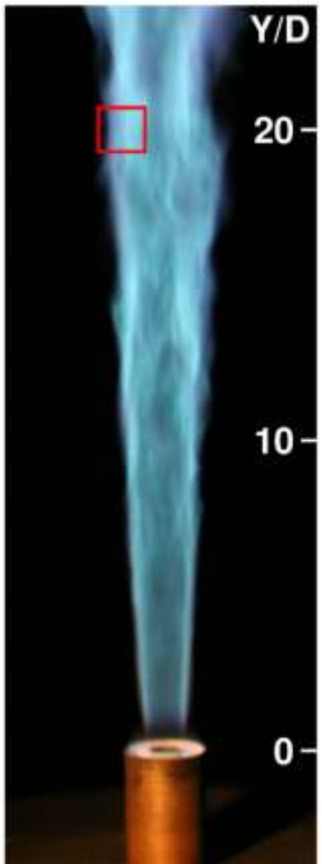


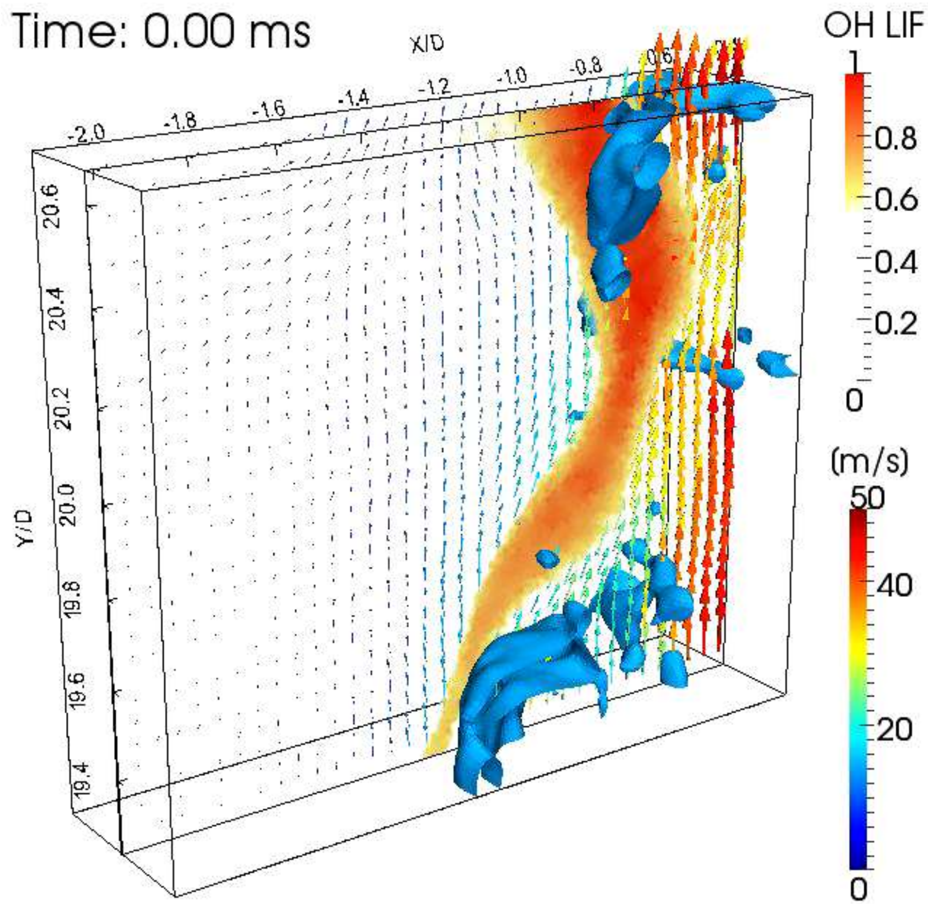
Volume Cross-Correlation



Compressive Strain Rate in Turbulent Partially-Premixed Jet Flames

Turbulent DME/Air Flame (Re_D ~ 29,300)





Strain rate isosurfaces for $|s| = 15{,}000\ s^{-1}$

Strain Rate Intermittency and Clustering

The level of localized extinctions in turbulent flames may well depend on the ***agglomeration, occurrences and lifetime*** of structures of very high strain rate.

Objectives

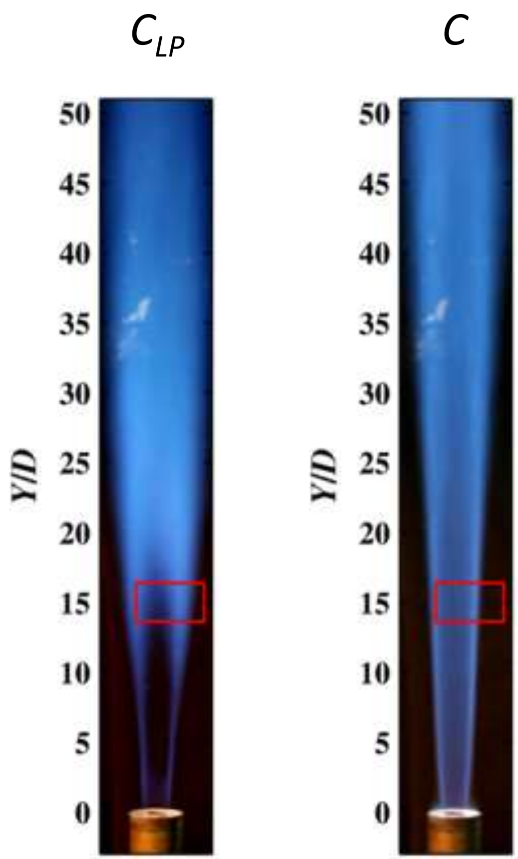
- Quantify the clustering and intermittency of elevated strain rate structures
- Evaluate the influence of combustion on the strain rate field

Approach: high-speed tomographic PIV

- Measure properties of strain rate in turbulent jets
- Compare the strain rate field in 3 turbulent jets of similar Reynolds numbers:
  - stable turbulent flame
  - unstable turbulent flame with frequent extinctions
  - turbulent air jet

Flow Conditions

Turbulent Flames

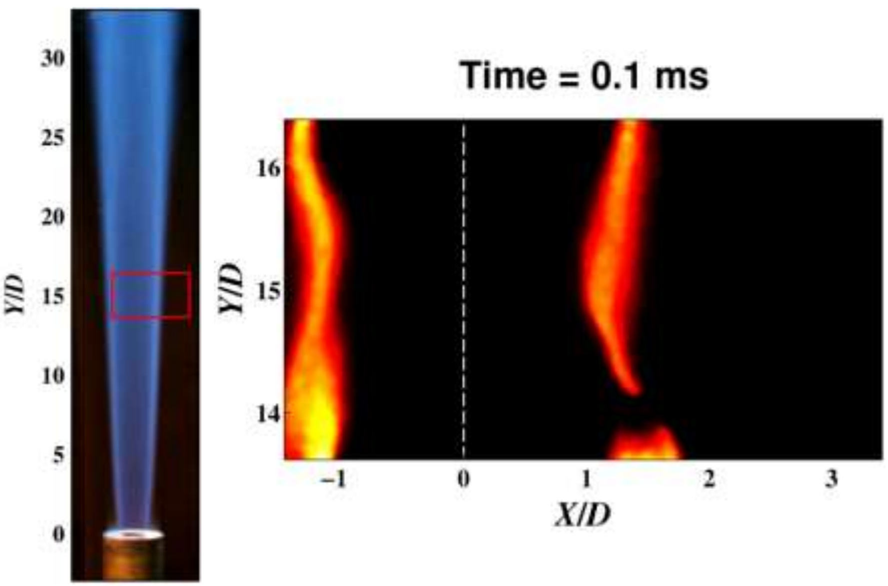


Cases	*Air Jet*	*Flame C_{LP}*	*"Sandia" Flame C*
Air/Fuel	N/A	3	3
V_{jet} (m/s)	27.5		
Re_{jet}	13,500	13,000	
V_{pilot} (m/s)	0.0	1.8	6.8

"Sandia" Flame C – Ref.: Barlow and Frank, 1998

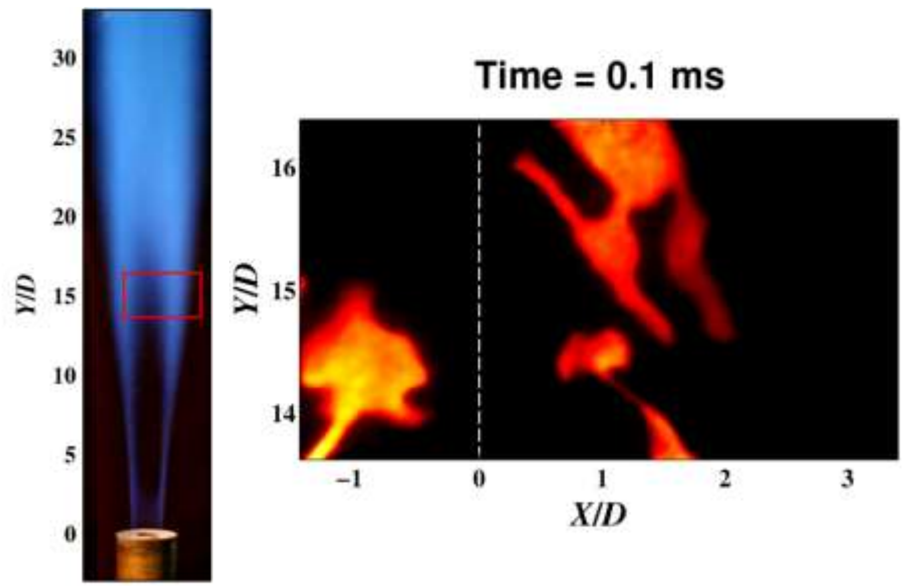
10 kHz OH PLIF Recordings of Flames C and C_{LP}

Flame C



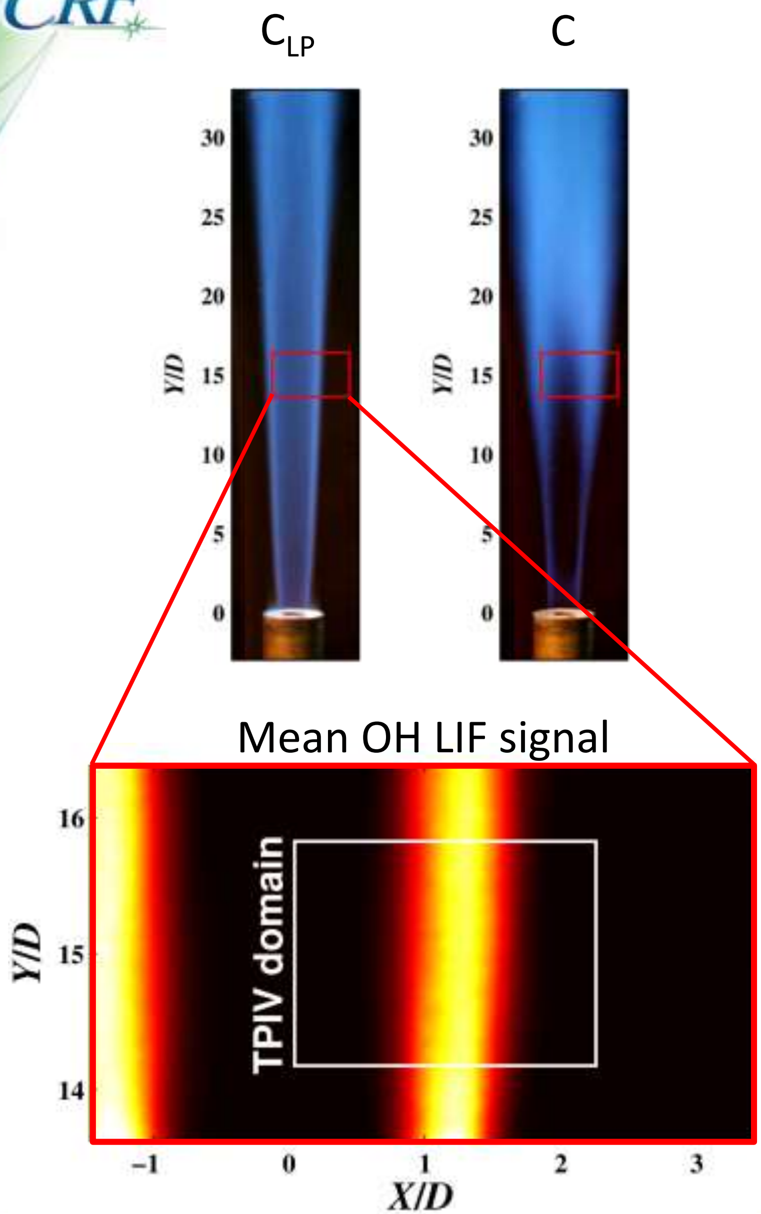
Flame is stable with rare occurrence of localized extinctions

Flame C_{LP}

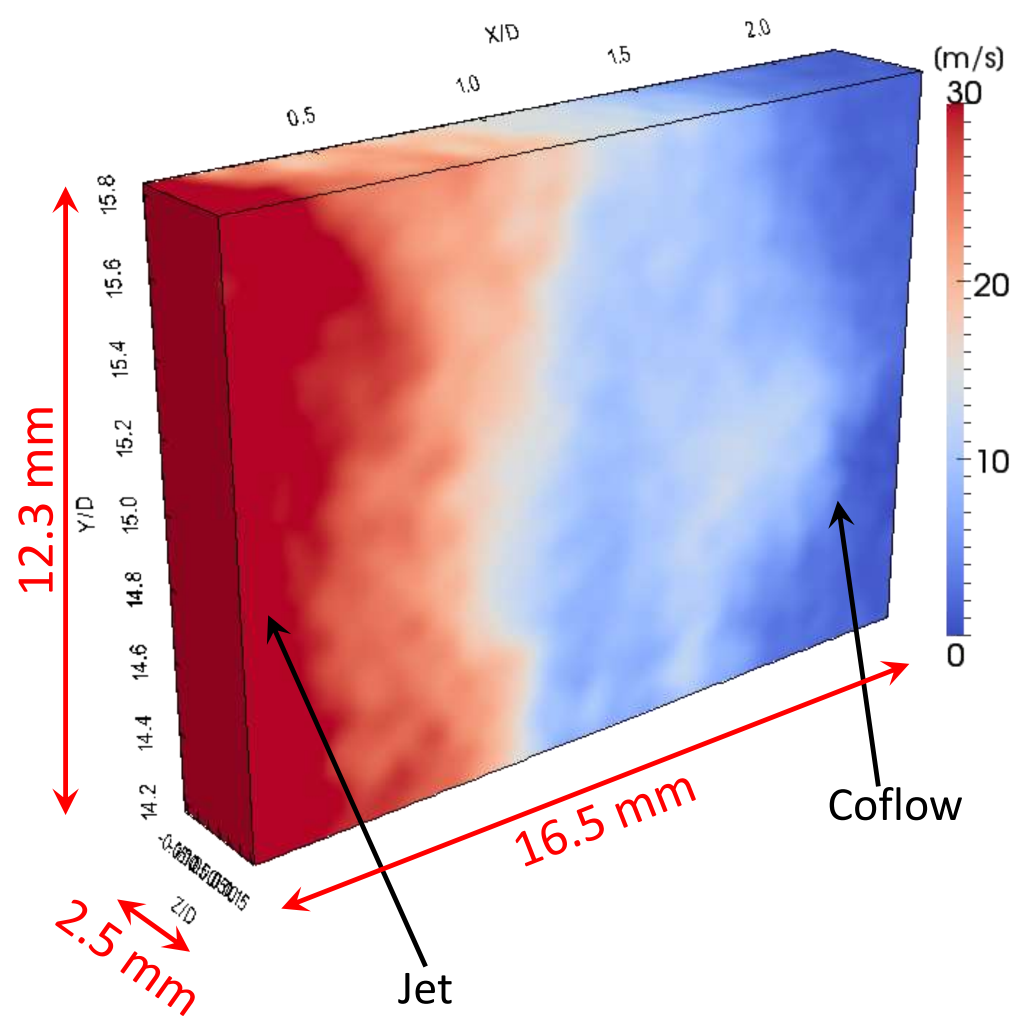


High probability of localized extinction and intermittent blowoffs

Probe Volume Location

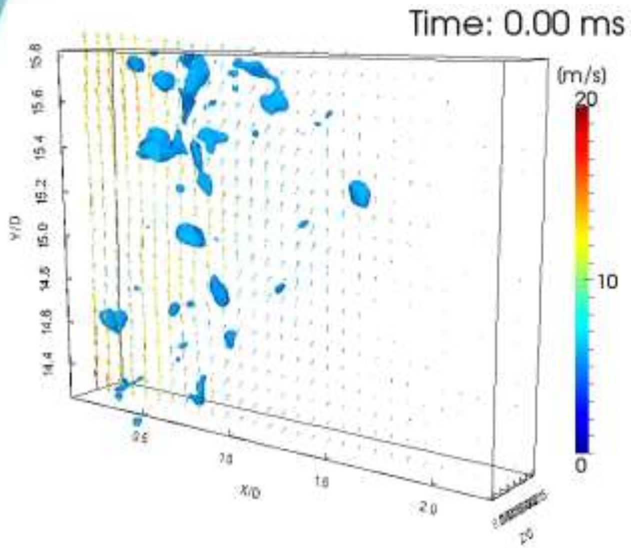


Probe Volume

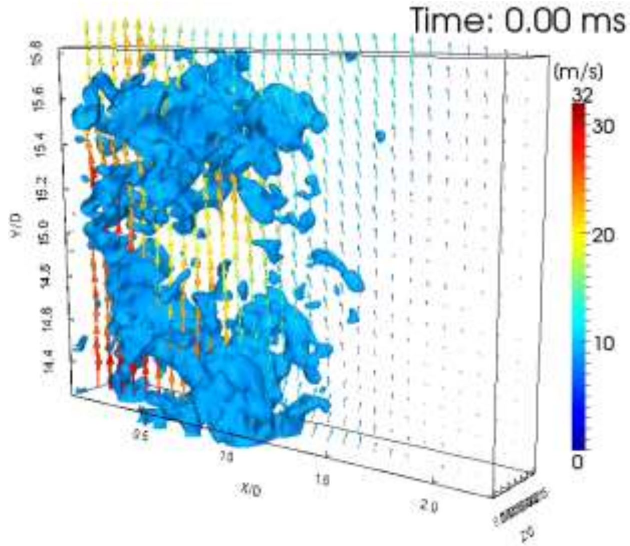


Bursts of Strain Rate Structures

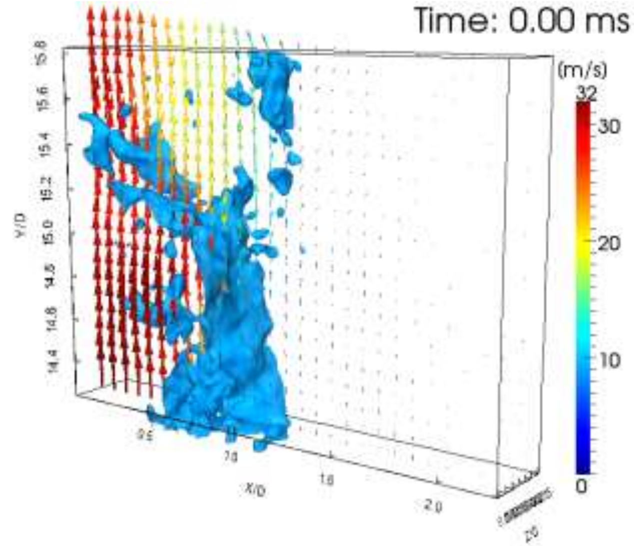
Air Jet



Flame C_{LP}



Flame *C*



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

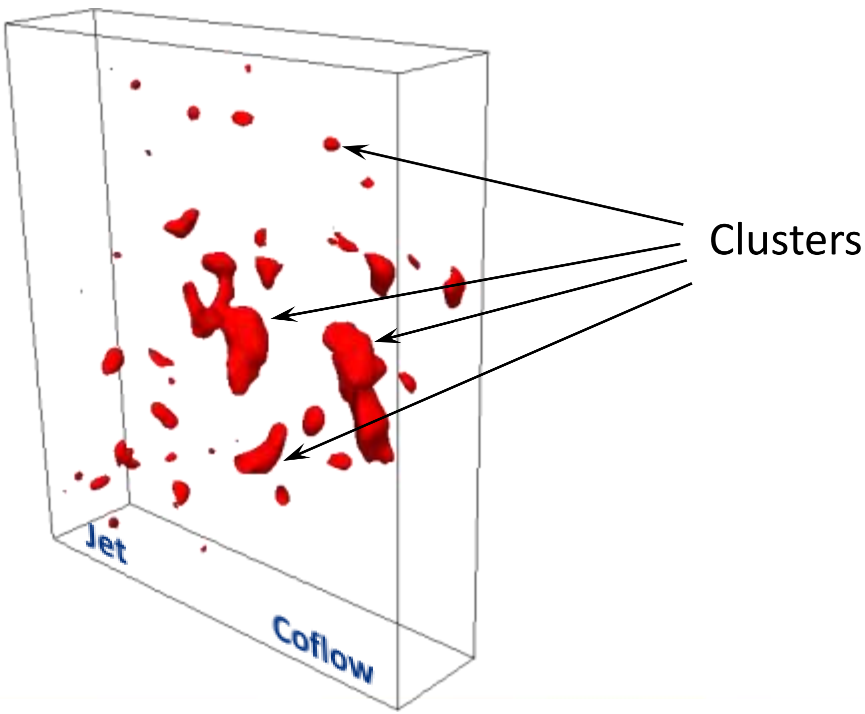
- Bursts of strain rate
- Spotty structures in the core of the *Air* jet
- Large elongated structures in the flames
- Flame C_{LP} has features of both the *Air* jet and Flame *C*

How to quantify the agglomeration of strain rate structures?

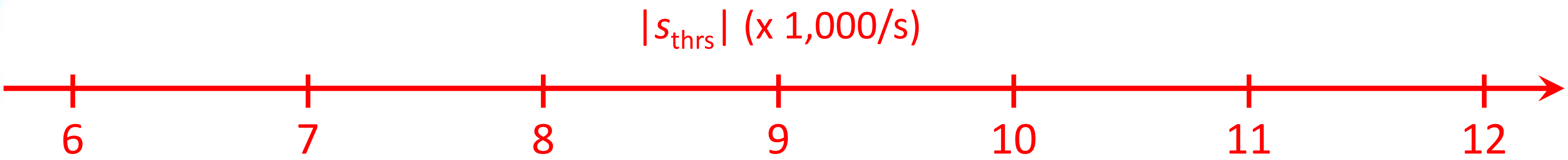
- A ***cluster*** is a singly-connected group of voxels where $|s| > |s_{thrs}|$.
- $N_c(t)$ = number of clusters in probe volume at an instant t.

Turbulent *Air* Jet

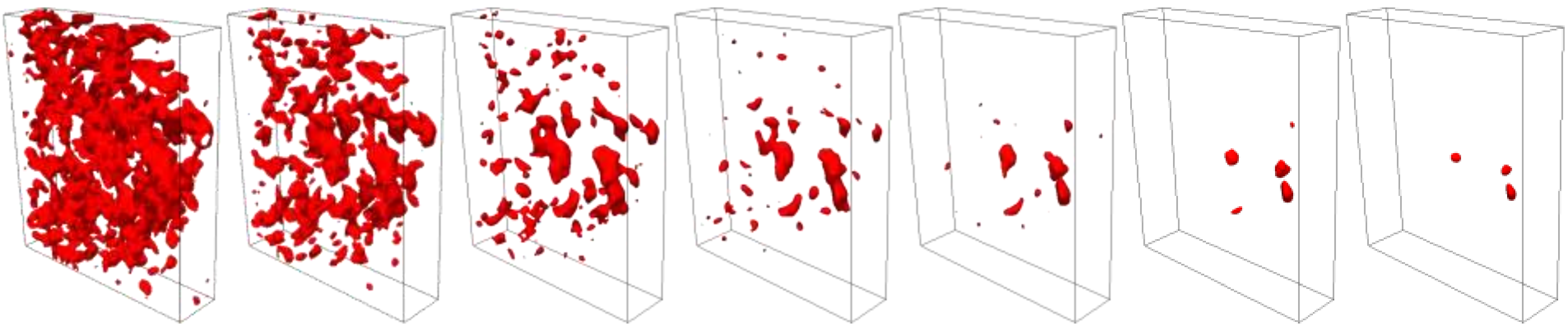
Isosurfaces for
$|s_{thrs}| = 9{,}000\ s^{-1}$



Visualization of Strain Rate Clusters

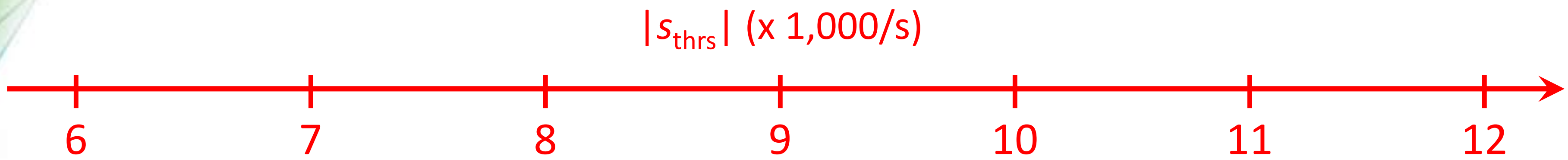


Turbulent *Air* Jet

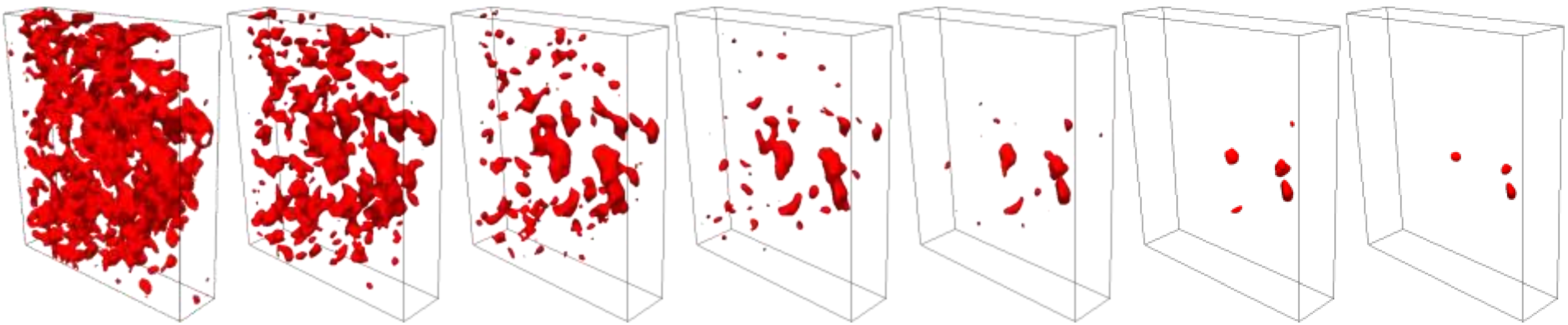


N_c varies with both time and |s_{thrs}|.

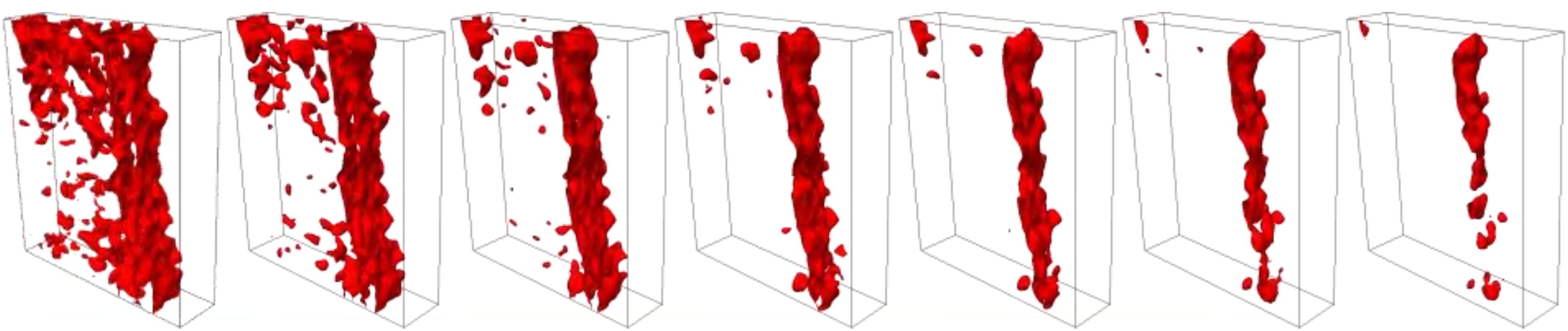
Visualization of Strain Rate Clusters



Turbulent *Air* Jet

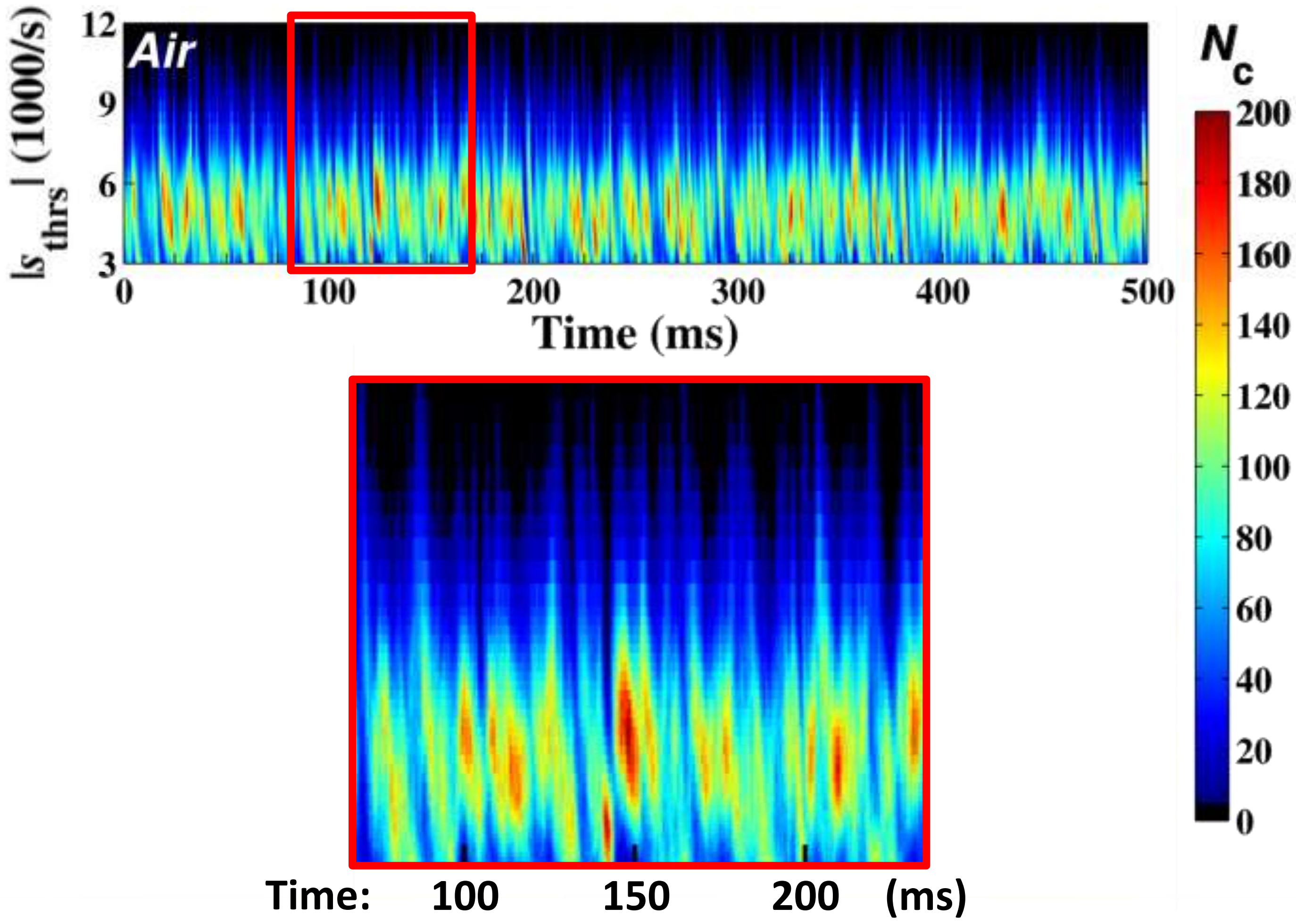


Turbulent Flame *C*



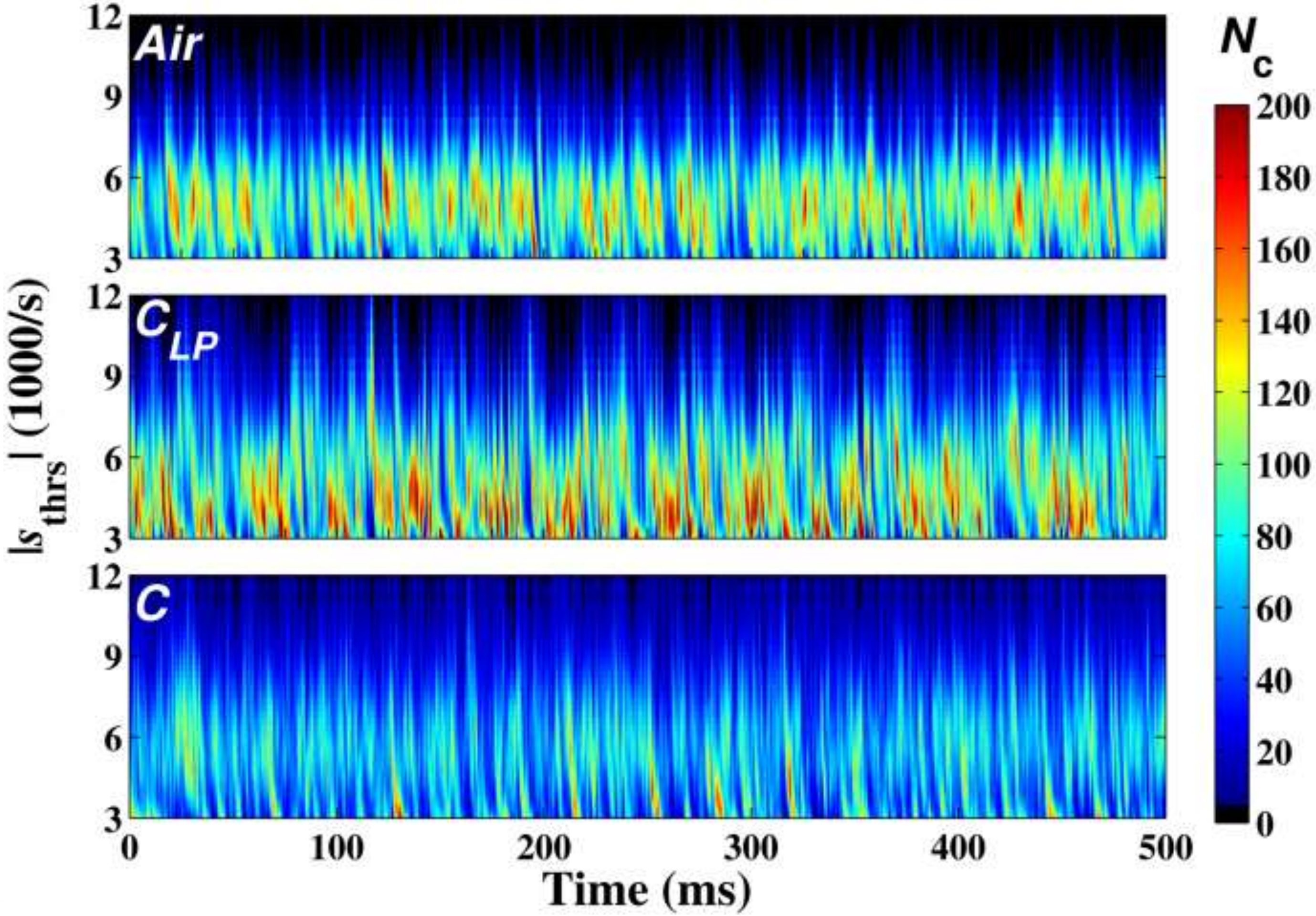
Bursts of Strain Rate Structures

- Intermittent appearances of high strain rate structures.



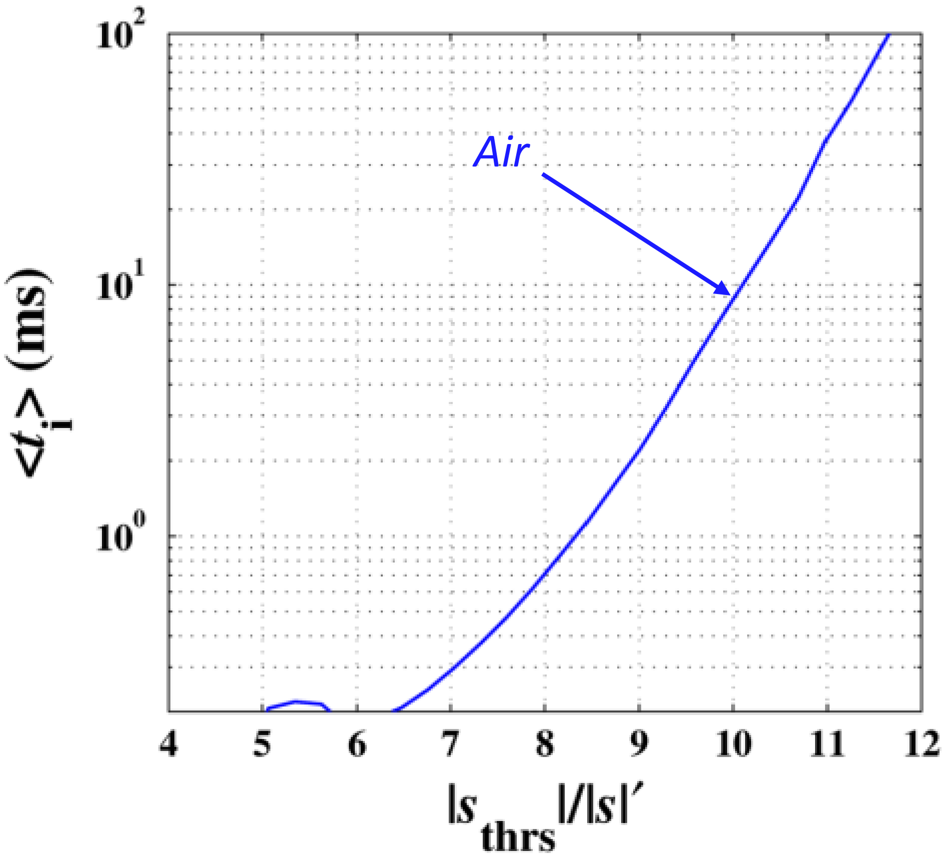
Bursts of Strain Rate Structures

- Intermittent appearances of high strain rate structures.
- Strain rate field is less connected in flame *C* than in *Air*.



Temporal Intermittency

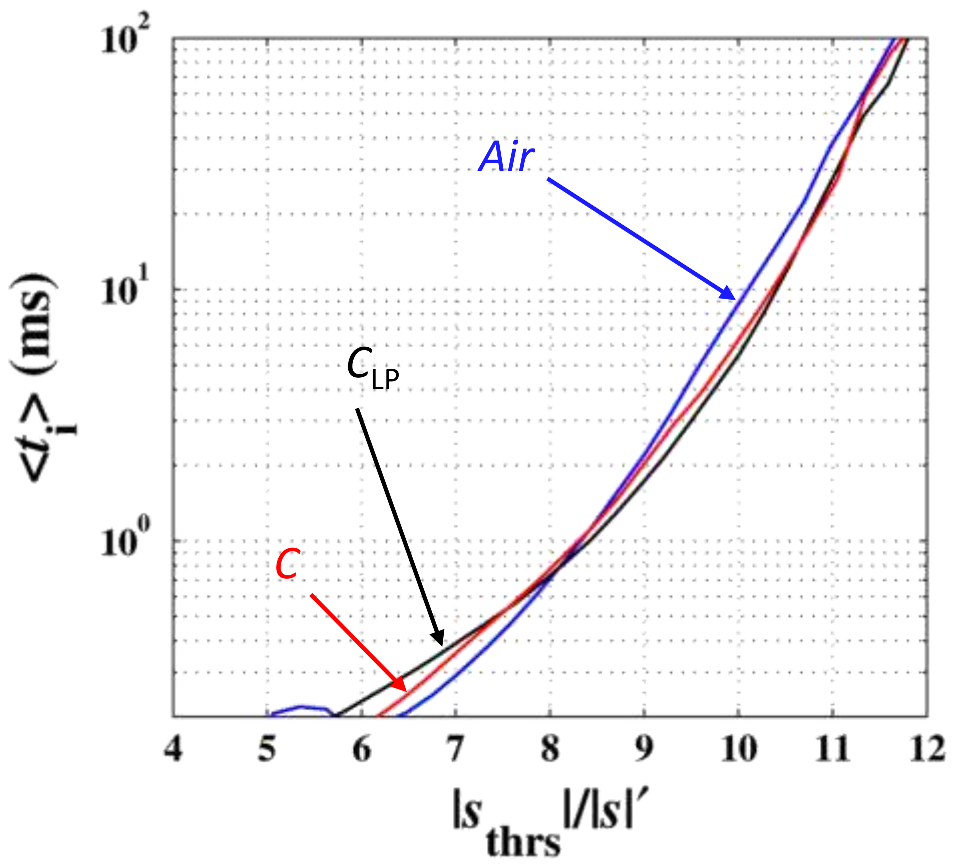
t_i = time interval between appearances of clusters



- $<t_i>$ ~ 0 ms for $|s_{thrs}| < 5|s|'$
- Structures for $|s_{thrs}|$ increasing above $5|s|'$ become rapidly intermittent.

Temporal Intermittency

t_i = time interval between appearances of clusters



- $<t_i>$ ~ 0 ms for $|s_{thrs}| < 5|s|'$
- Structures for $|s_{thrs}|$ increasing above $5|s|'$ become rapidly intermittent.
- Combustion has negligible effect on temporal intermittency.

Part III – Summary

- High-speed tomographic PIV has the potential to unveil new information on the dynamics of turbulent flames at both the fundamental and practical levels.

- All the components of the gradient tensors are determined (vorticity, strain rate, invariants of the gradient tensor).

- Reduced uncertainty of out-of-plane motion and bias of 2D measurements in turbulent flows

- Identification and tracking of coherent structures and their interaction with flame fronts.

Part III – Impact

1st Demonstration of high-speed, tomographic PIV in reactive flows

- 8th US National Combustion Meeting, 2013
- Gordon Research Conference, 2013
- 35th International Symposium on Combustion, 2014

Peer-reviewed publications:

- **B. Coriton** and J.H. Frank, Proc. Combust. Instit. 36 (2016), *under review*.
- **B. Coriton** and J.H. Frank, Phys of Fluids (2016), *in press*.
- **B. Coriton** and J.H. Frank, Proc. Combust. Instit. 35 (2015).
- A.M Steinberg, **B. Coriton**, J.H. Frank, Proc. Combust. Instit. 35 (2015).
- **B. Coriton**, A.M. Steinberg, J.H. Frank, Exp. Fluids 55:1743 (2014).

Collaborations:

- Nicholas Ouellette (Yale University)
- Dula Parkinson (Lawrence-Berkeley National Labs)
- Adam M. Steinberg (University of Toronto)

Concluding Remarks

- Combustion will continue to provide a major portion of the world energy mix in the future.
- Fundamental understanding of combustion is necessary to develop future combustion technologies.
- The improvement of laser and imaging diagnostics make the study of advanced combustion processes possible.