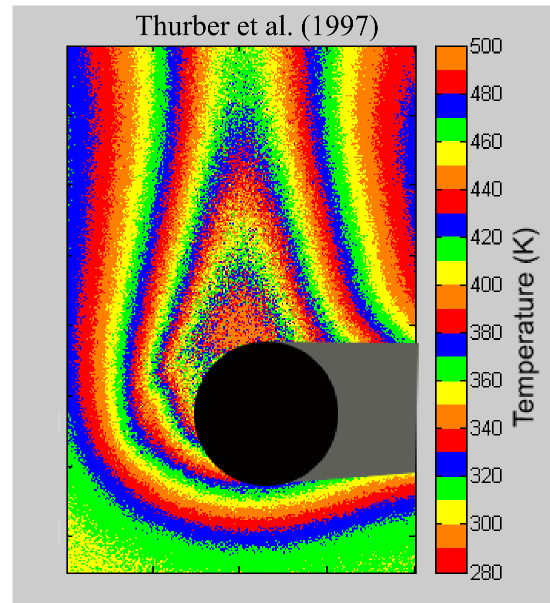
Quantitative Laser Diagnostics for Combustion Chemistry and Propulsion

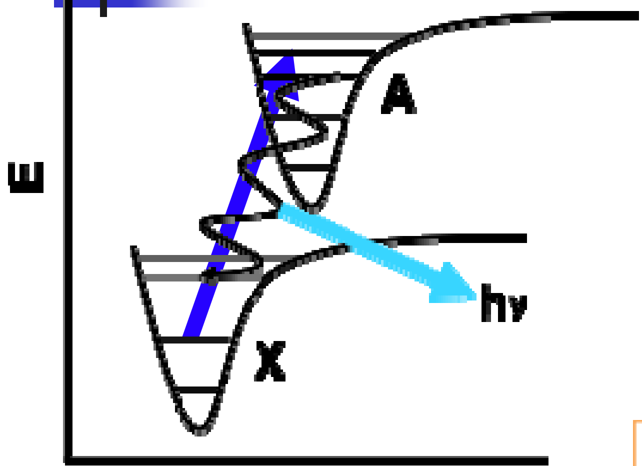
Lecture 15: Application Examples of LIF, PLIF Large Molecules (Tracers)

1. Introduction to flow tracer PLIF
2. Acetone PLIF to image fuel mixing
3. 3-pentanone PLIF as a flow tracer
4. 3-pentanone PLIF in IC-engines
5. CW PLIF for high-frame-rate imaging
6. Toluene PLIF for temperature (1 camera)
7. Toluene PLIF for temperature (2 camera)
8. The future



Temperature image; single-shot PLIF of acetone in flow around heated rod

1. Introduction to Flow Tracer PLIF

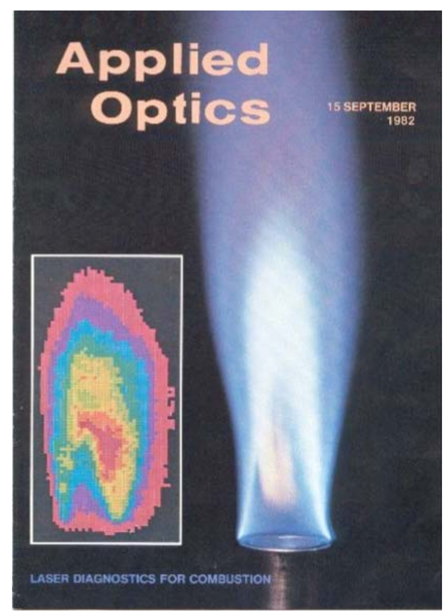


Planar Laser-Induced Fluorescence

$$\underbrace{S_f}_{\text{LIF Signal}} = \underbrace{\frac{E}{h\nu}}_{\text{Incident Photons}} \underbrace{n\sigma(\lambda,T)}_{\text{Photons Absorbed}} \underbrace{\phi(\lambda,T,p_i)}_{\text{Fluorescence Quantum Yield}} \underbrace{\eta}_{\text{Collection Efficiency}}$$

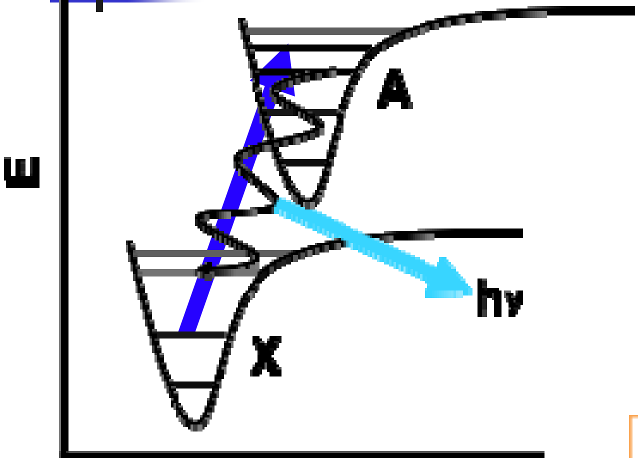
- History of PLIF begins at Stanford 1982 - Kychakoff, Howe, Hanson, and McDaniel using OH

- Now we examine PLIF from tracers, mostly ketones, to control ϕ



1. Introduction to Flow Tracer PLIF

LIF of tracer molecules added to flow



Planar Laser-Induced Fluorescence

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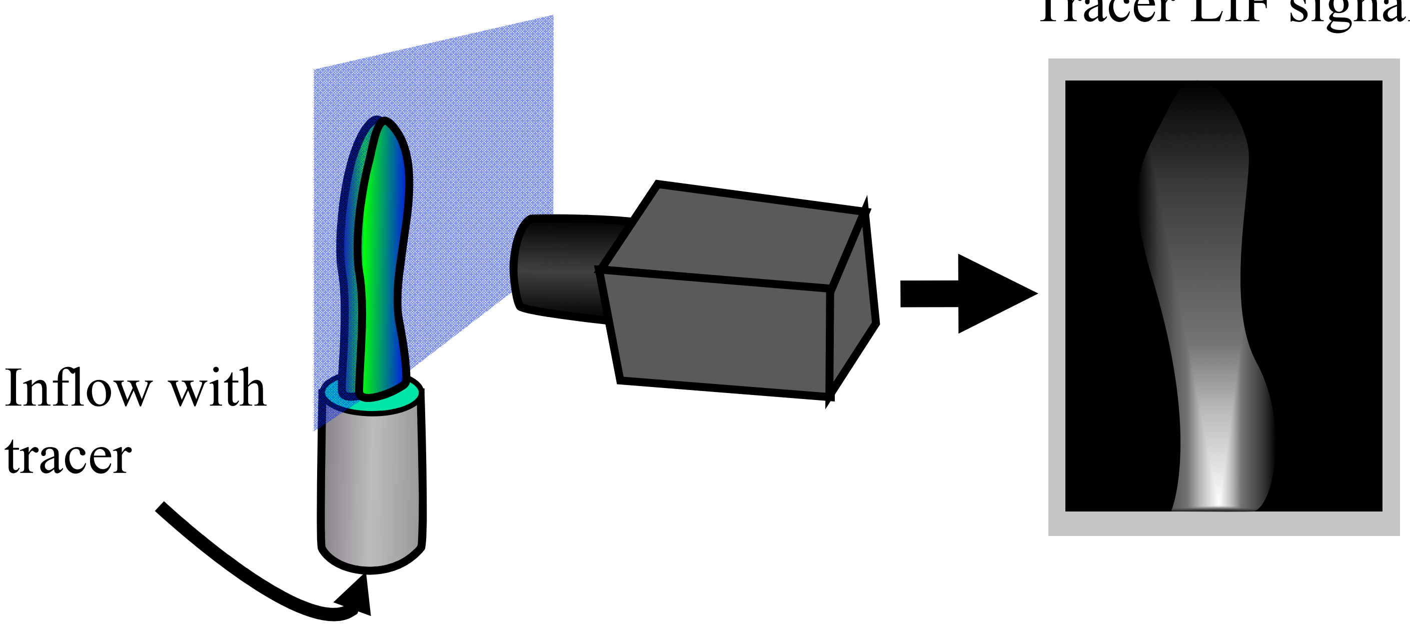
LIF Signal: S_f

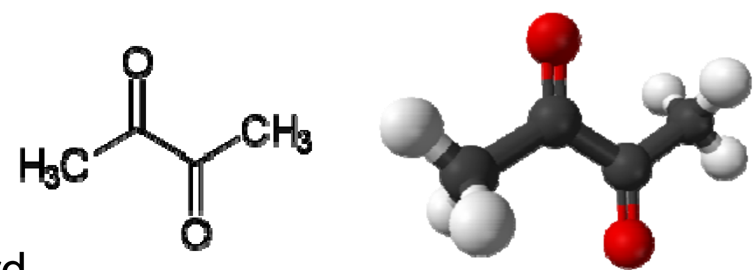
Tracer LIF signal



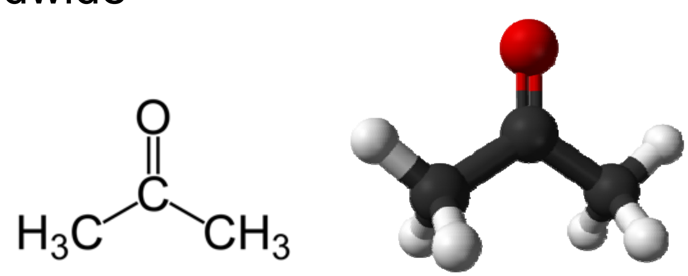
1. Introduction to Flow Tracer PLIF
Biacetyl and acetone first tracers used

- Background: Addition of a fluorescent tracer enabling LIF and PLIF in air (neither O_2 nor N_2 are readily accessible)

  - 1980's at Stanford HTGL
    Biacetyl ($(CH_3CO)_2$), but had two problems:
    1) smelly and hard to handle
    2) highly quenched by O_2

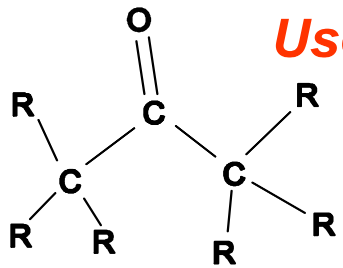


  - Early 1990's by Lozano at Stanford
    Acetone (CH_3COCH_3), has become a popular laser diagnostic in laboratories worldwide



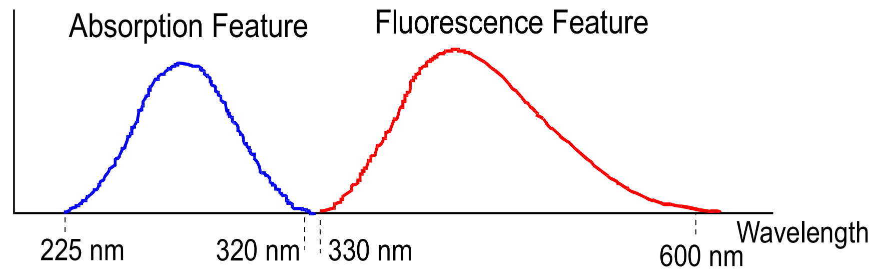
1. Introduction to Flow Tracer PLIF
Ketones are good flow tracers

- How can PLIF be used to study mixing?



Ketone

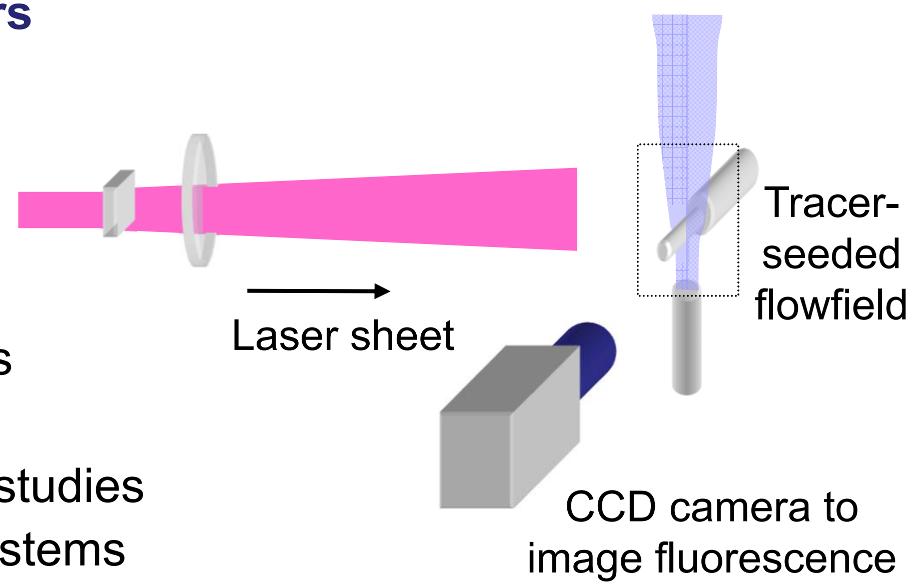
Use Ketones as Tracers: Acetone and 3-Pentanone



- **Advantages of Ketones as Tracers**

+ Strong signals
  - Accessible absorption feature
  - Non-resonant fluorescence
+ Resistant to bath gas effects
+ Similar to common hydrocarbon fuels

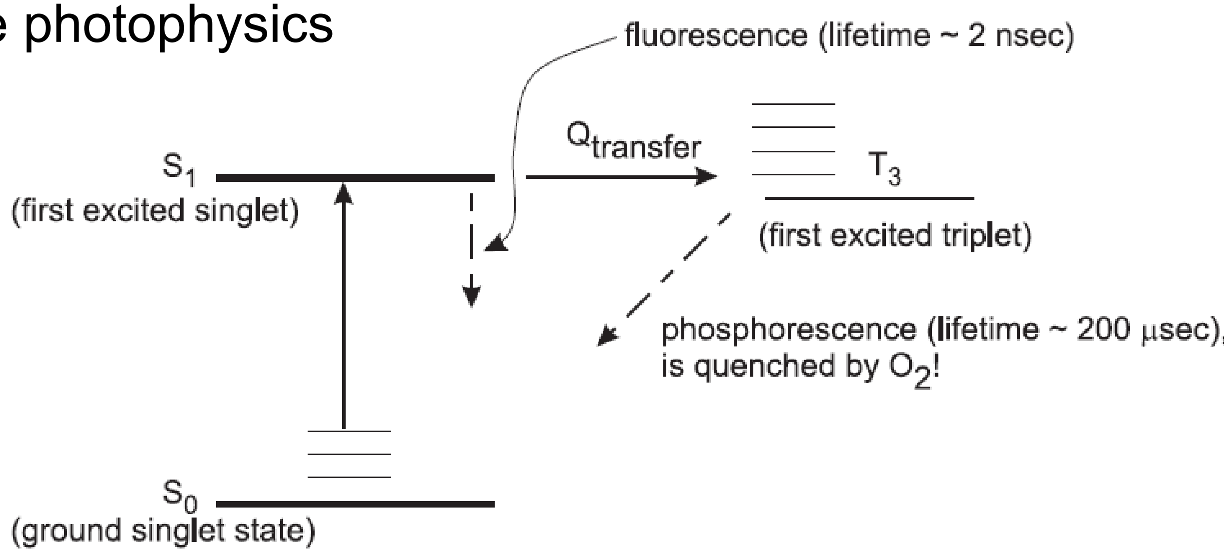
- **Applications**
  - Fundamental fluid/heat transfer studies
  - Fuel/air mixing in combustion systems



➡ *Application is straightforward in isothermal, isobaric flows , i.e., Signal is proportional to mixture fraction of tracer*

1. Introduction to Flow Tracer PLIF
A brief overview of acetone LIF

- Acetone photophysics

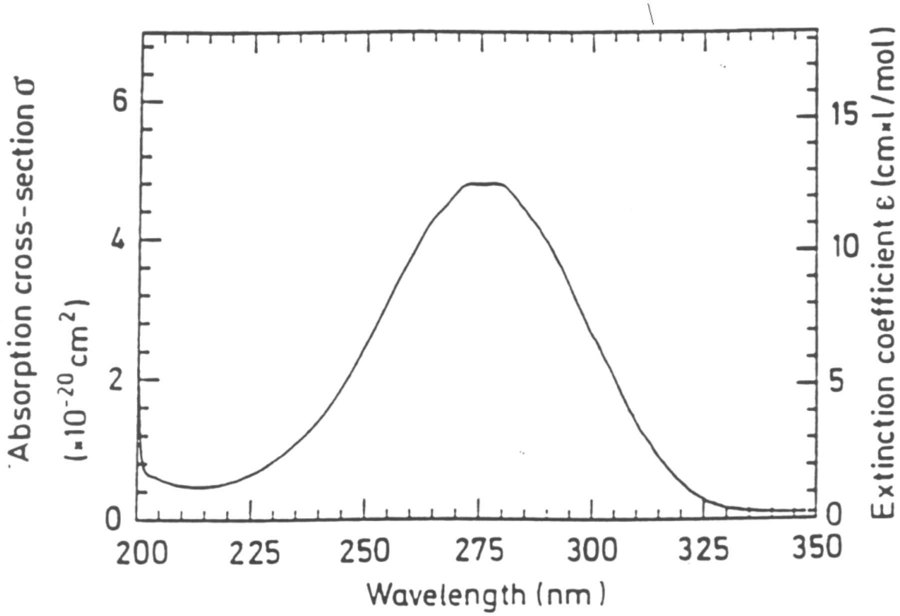


  - Vapor pressure is 180Torr at room temperature
  - Cheap, non-toxic, easy to handle
  - Fluorescence lifetime is approximately 2ns and is independent of O_2
  - Constant fluorescence yield of about 0.2% at room temperature
  - Each state is a manifold of vibrational levels
  - "Intramolecular intersystem crossing" at rate Q_t dominates, therefore the FY = $A_{10}/(A_{10} + Q_t) \approx A_{10}/Q_t \approx 0.2\%$ and SF $\propto n_{acetone}I_\nu$(or E)!
  - Absorption and fluorescence are broadband

2. Acetone PLIF to Image Fuel Mixing

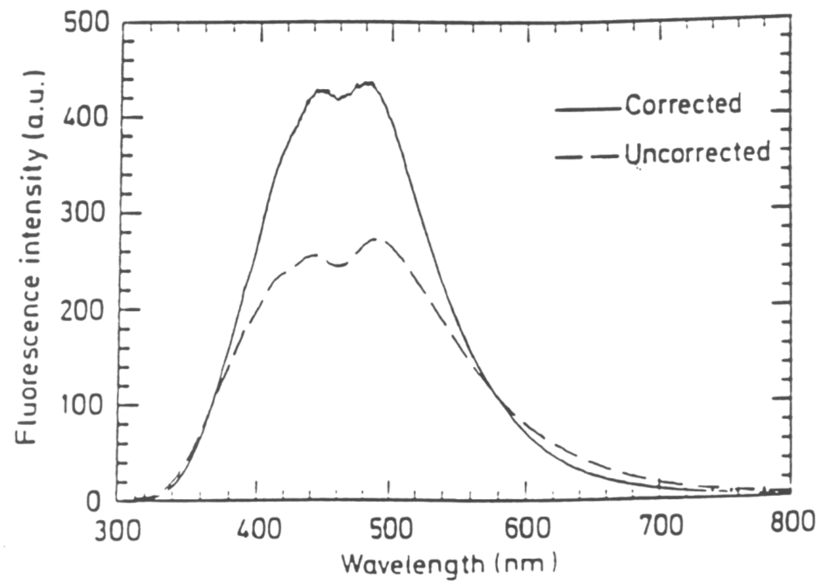
Absorption and fluorescence wavelengths

- Acetone: A tracer for concentration measurements in gaseous flows by planar LIF (Lozano, Yip & Hanson, 1992)



Acetone absorption spectrum corresponding to excitation from the ground state to the first excited singlet

- Reveals range of suitable excitation wavelengths



Acetone fluorescence spectrum when excited at 308nm: the dashed line corresponds to the detected signal; the solid line is the same curve corrected for the detection system responsivity

- Reveals separation of emission wavelength from excitation

2. Acetone PLIF to Image Fuel Mixing

- Example of acetone PLIF to investigate jet in crossflow: isothermal, isobaric mixing study

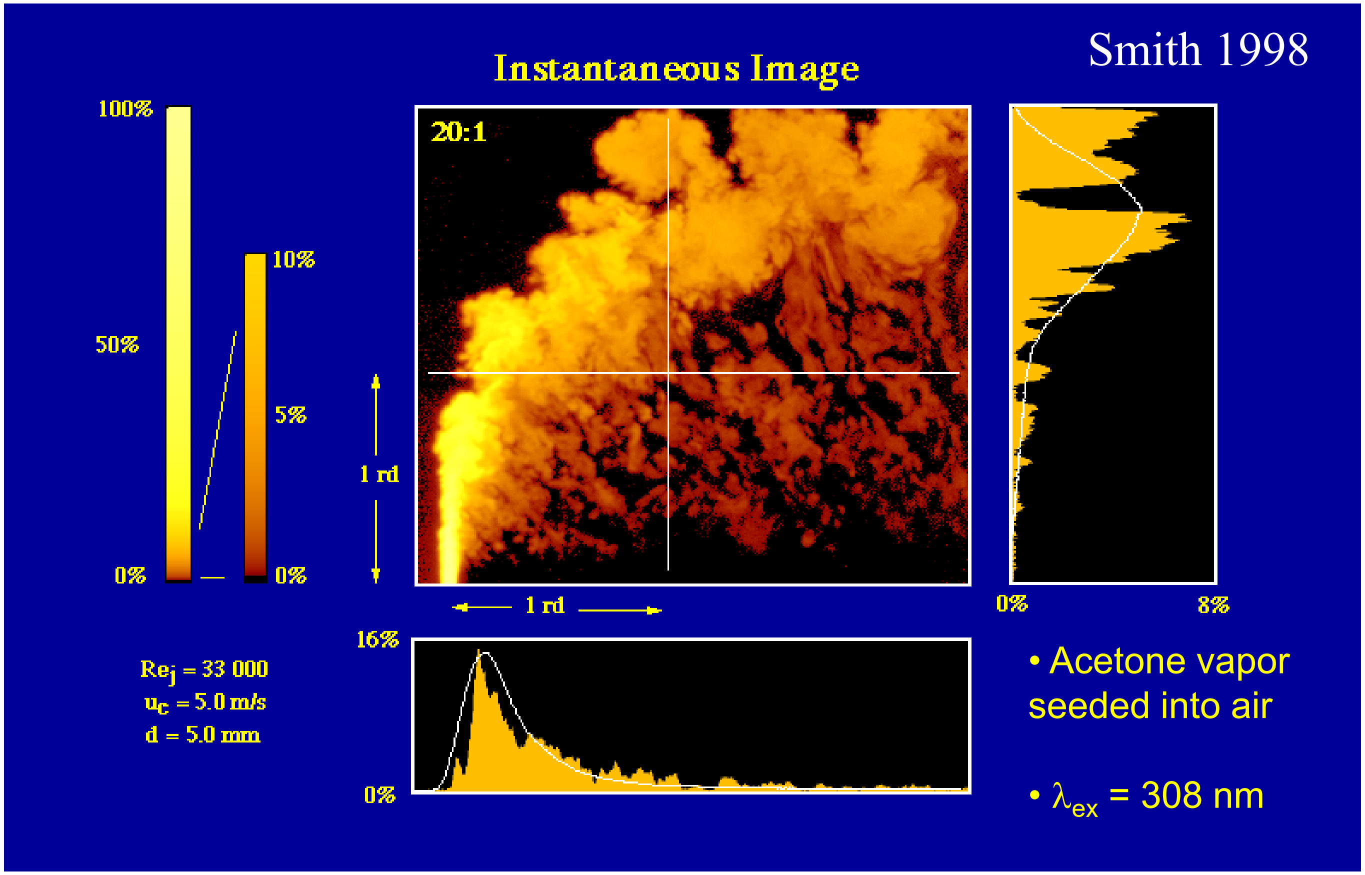
Side-view

$U_{crossflow}$=5 m/s

d_{jet}=5 mm

$U_{jet}/U_{crossflow}$=20/1=r

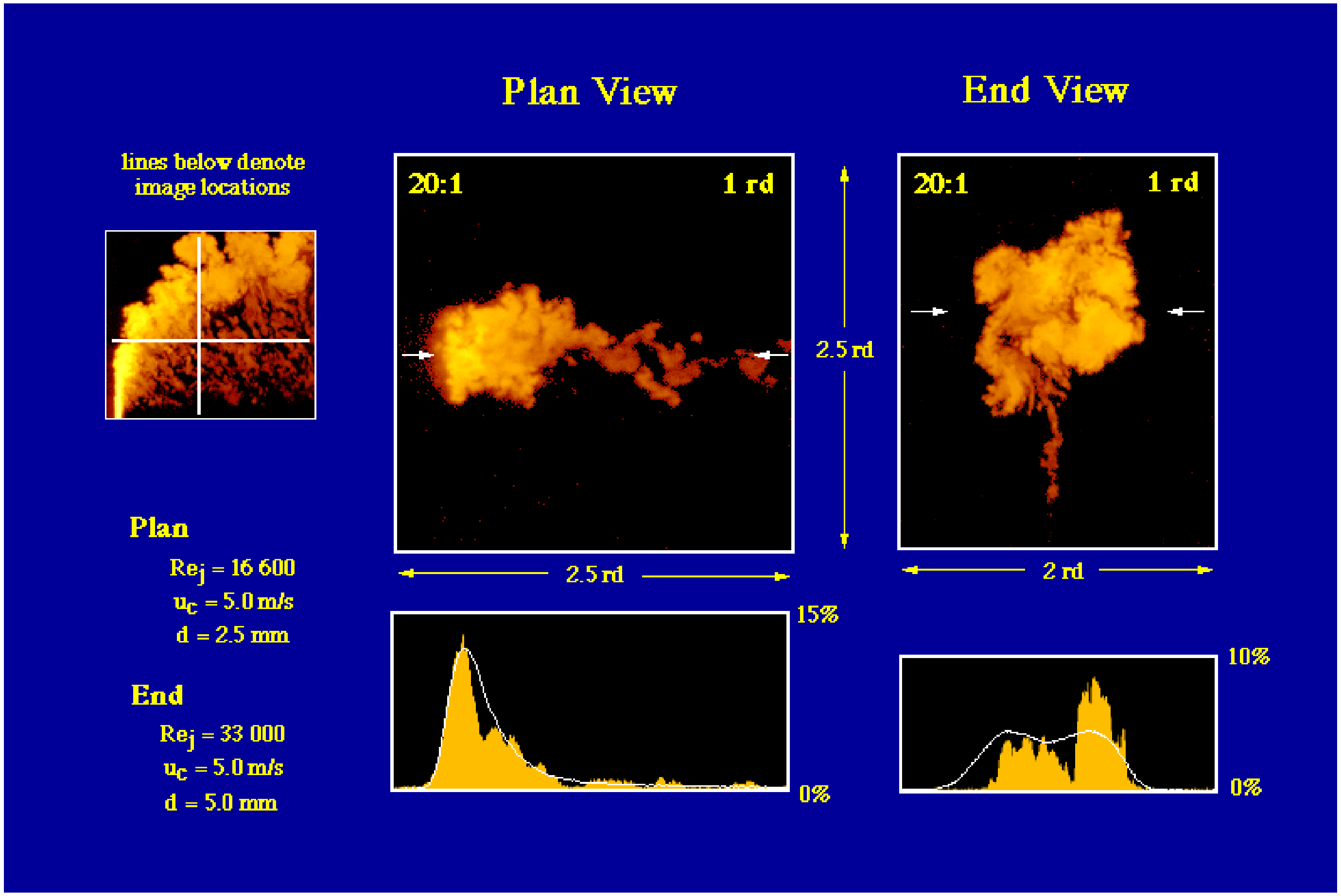
1 rd = 10 cm



- For isothermal, isobaric case, fluorescence signal is proportional to tracer mole fraction

2. Acetone PLIF to Image Fuel Mixing

- Example of acetone PLIF to investigate jet in crossflow: isothermal, isobaric mixing study



- Detail provided by PLIF provides important tests of model predictions

3. 3-pentanone PLIF as a Flow Tracer

Photophysics Database and Modeling: Fundamentals

- PLIF with ketone/aromatic tracers widely used, but not quantitative at high P & T

S_f	=	$E/h\nu$	x	L	x	n_{ab}	x	$\sigma(\lambda,T)$	x	$\phi(\lambda,T,P)$	x	$\eta\Omega/4\pi$
signal		number photons		path length		number density		absorption cross-section		fluorescence yield (FQY)		collection optics

$$\underbrace{\sigma(\lambda,T) \times \phi(\lambda,T,P)}_{\text{Photophysical parameters}}$$

- Measurements and modeling needed for *s(l,T)*, *f(l,T,P)* at high P & T

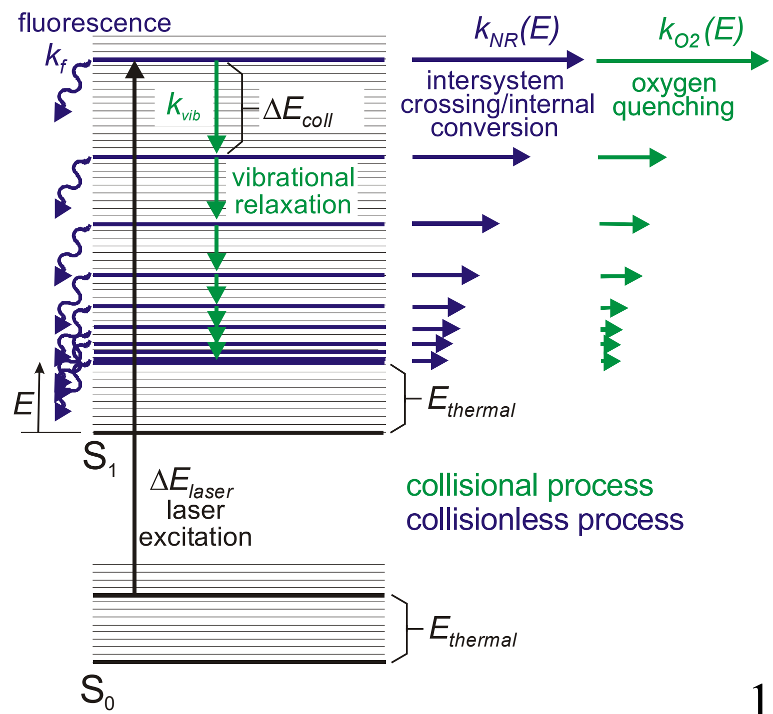
$$\phi = \sum_{n=0}^{\infty} \frac{k_f}{k_f + k_{vib} + k_{nr}(E_n) + k_{O2}(E_n)} p(E_n)$$

k_{vib} = collisional rate (s^{-1})

n = n^{th} collisional time step

Energy at n^{th} step: $E_{n+1} = E_n - \Delta E_{coll} = E_n - \alpha(T)[E - E_{thermal}]$

- Model has four parameters, α, k_{nr}, k_{O2}, k_f
  - k_{nr} & k_{O2} measurable from lifetime data
  - α, k_f from f data over range of P,T

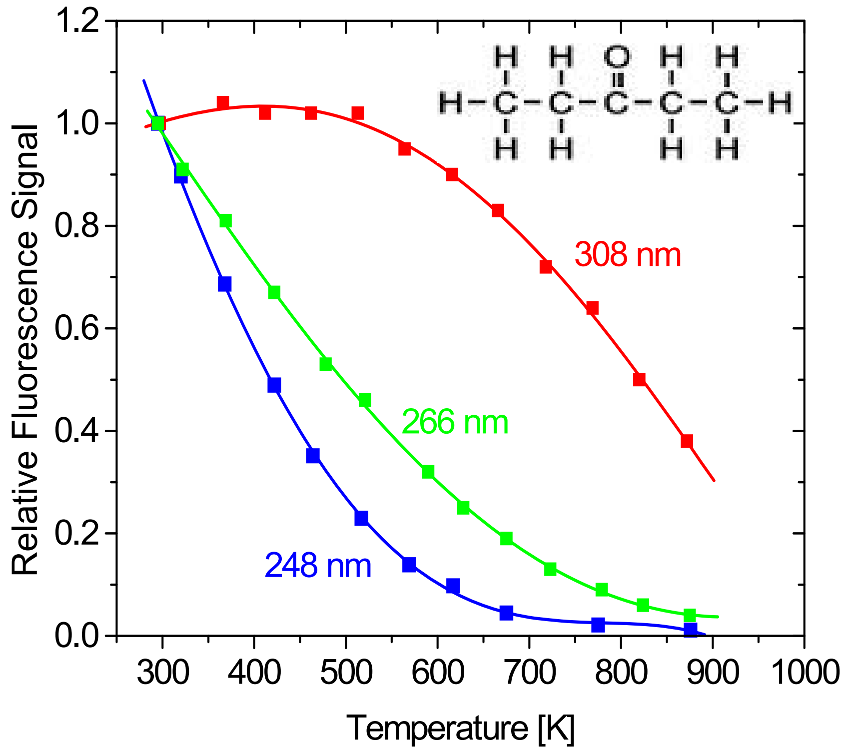


3. 3-pentanone PLIF as a Flow Tracer

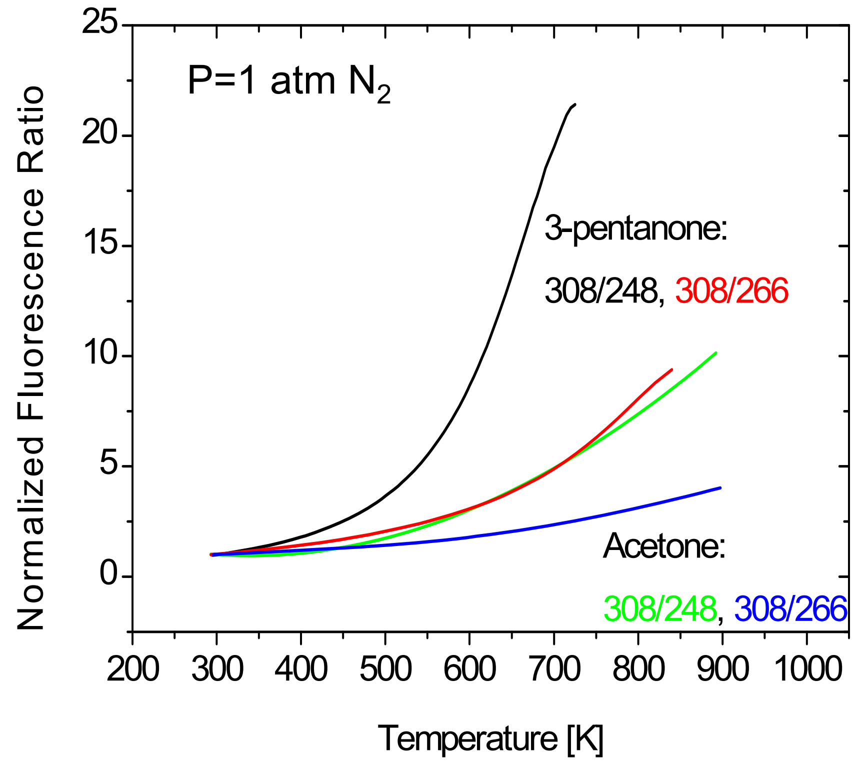
3-pentanone: Better match to physical properties of fuels

Photophysical behavior qualitatively similar to acetone but quantitatively different

3-pentanone
Single Excitation Wavelength



Acetone and 3-pentanone
Dual Excitation Wavelength



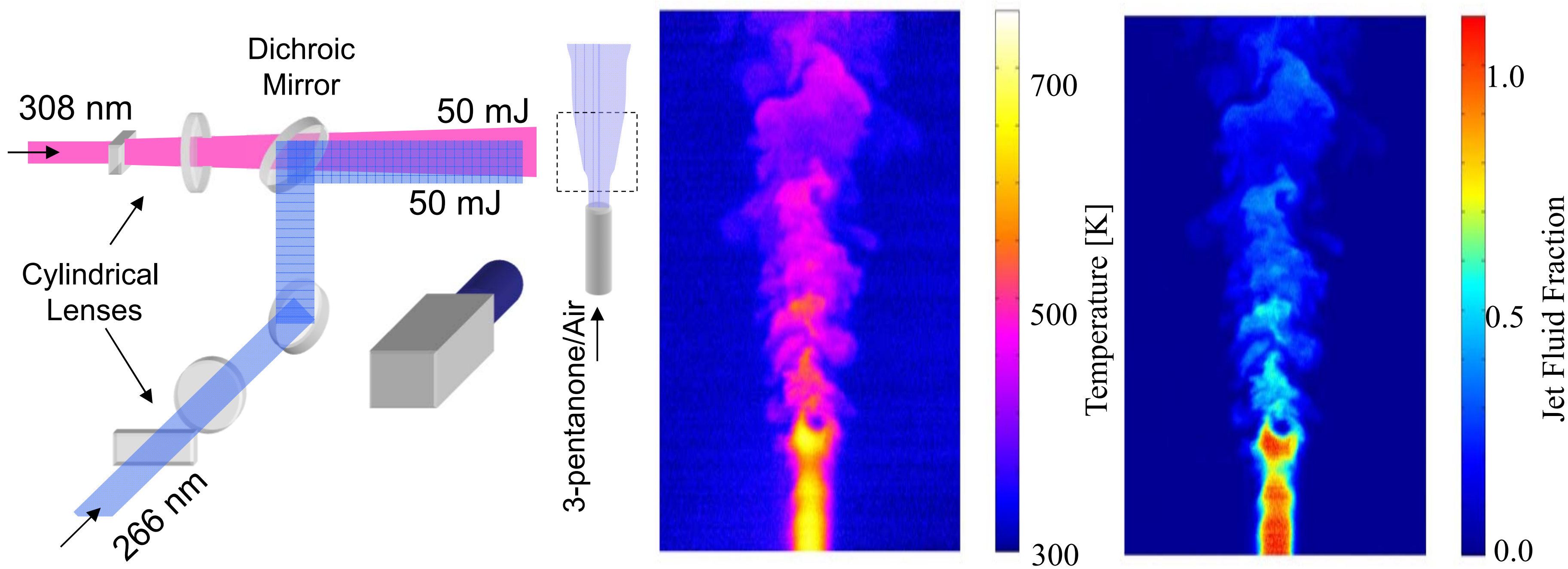
- 308 nm, T< 550K - ideal regime for straightforward concentration imaging
- 248 nm highly T-sensitive – good for temperature imaging

- Long/short wavelength ratios are most temperature sensitive
- 3-pentanone is more T-sensitive than acetone

3. 3-pentanone PLIF as a Flow Tracer

Simultaneous Imaging of χ_i, T

- Strong T dependencies of 3-pentanone enable quantitative imaging



Koch and Hanson 2003

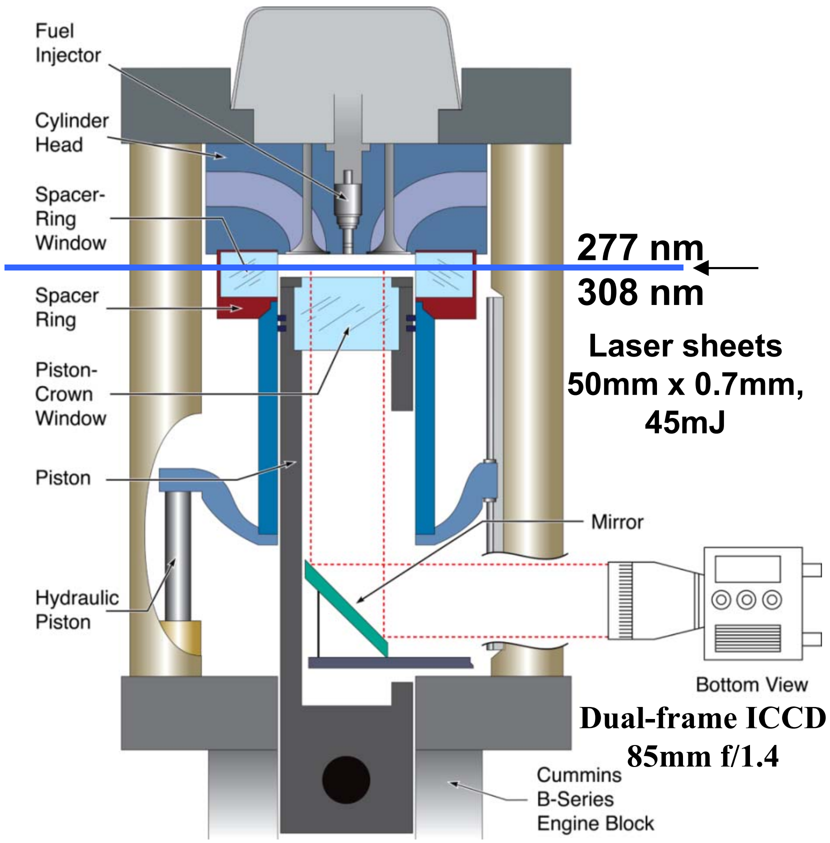
- Laser excitation at 308 and 266 nm
- Frame transfer CCD camera acquires 2 images within 2 μs

- Instantaneous T, χ_i images from a heated 3-p/air jet after 308/266 nm excitation
- Flowfield contains 1-4% 3-pentanone (2.9% is stoichiometric)

4. 3-pentanone PLIF in IC-Engines

Homogeneous Charge Compression Ignition (HCCI)

- Natural thermal stratification (TS) important for HCCI engine ignition
- Increase of TS could extend high-load operation
- PLIF of temperature and residuals an important tool to study TS



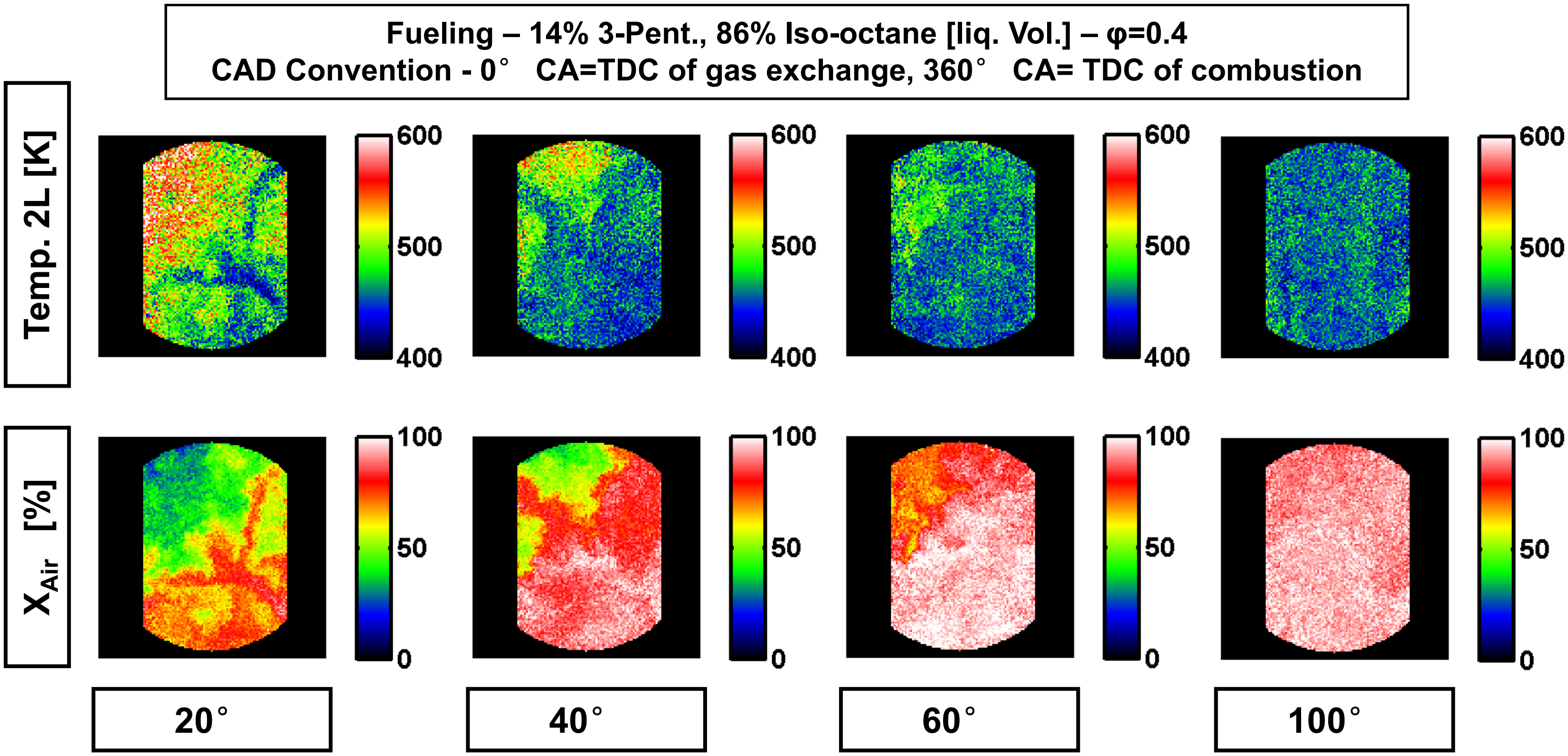
HCCI Engine Combustion Fundamental Laboratory, Sandia National Labs

- Tracer-based PLIF strategies used
  - Two-line (277nm/308nm ratio) – simultaneous T and χ_i
  - Single-line (277nm) – T (homogeneous composition)
  - Tracer selection: 3-Pentanone – good sensitivity, minimal effect of oxygen quenching
- Investigate the thermal stratification in HCCI engine: motored & fired operation
  - Early residual mixing
  - Thermal stratification evolution during compression

4. 3-pentanone PLIF in IC-Engines

Mixing of Residuals with Fresh Intake Can Produce Stratification

- Incomplete mixing of hot retained residuals (internal EGR) with fresh intake can result in TS
- Two-line PLIF of T and χ_{air} to track evolution of intake-air/residual gas mixing



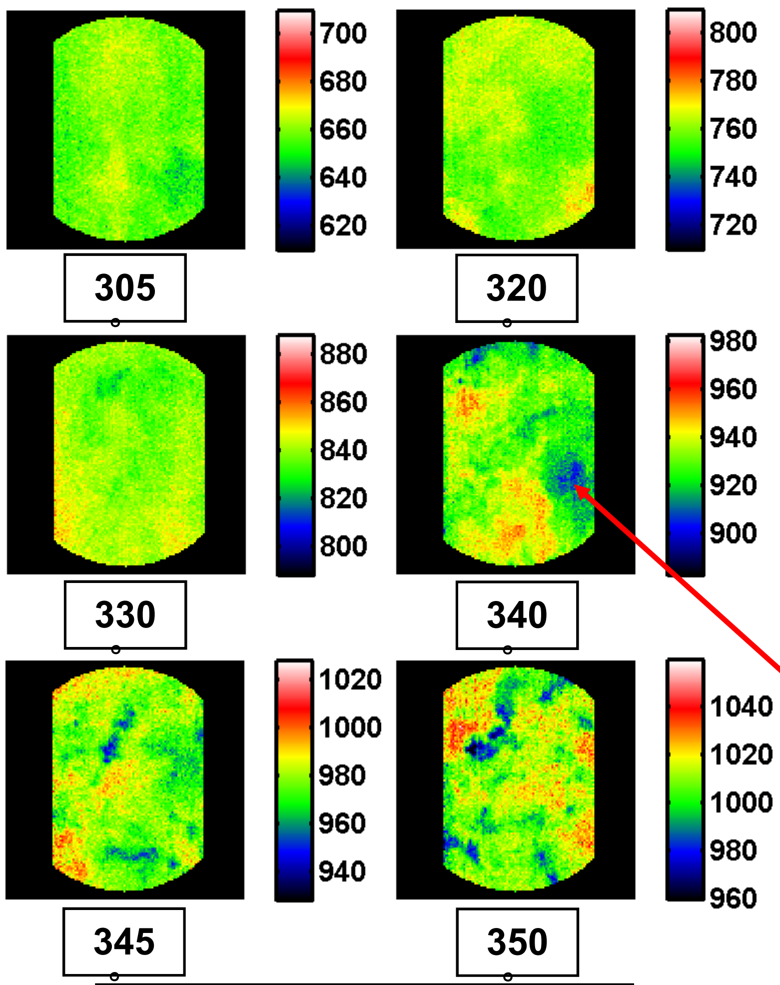
- Mixing complete after 100º of CA (bottom of stroke at 180º)
- Mixing of EGR and fresh intake does not increase the thermal stratification for these conditions

Snyder et al. 2011

4. 3-pentanone PLIF in IC-Engines

One-line PLIF in Engines:
Natural Thermal Stratification (TS) Increase Near TDC

Temperature [K]



Fueling – 14% 3-Pent., 86% Iso-octane [liq. Vol.] – φ=0.4

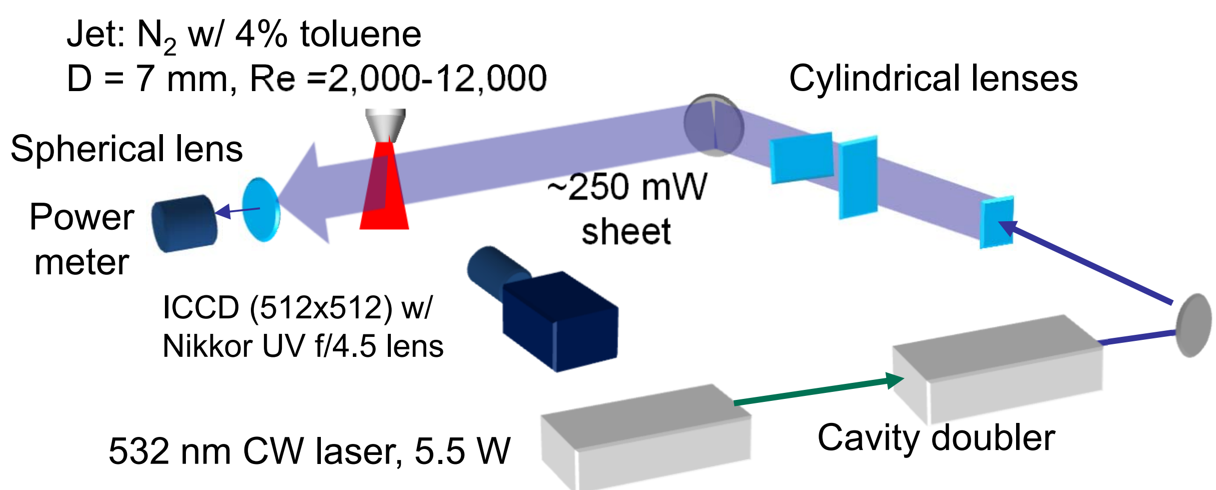
- Single-line (277nm) PLIF of temperature to monitor TS evolution during compression
- High sensitivity of measurement (4-5K) allows detection of small variations – important for HCCI
- Initial TS is small (305°CA) but drastically increases throughout remaining compression
  - TS near TDC results in sequential auto-ignition that reduces the rate of heat release – important for extension to high-load operation

Heat transfer with wall surfaces in boundary layer leads to pockets of cooler gas that convect into core cylinder region and affect auto-ignition

5. CW PLIF for High-Frame-Rate Imaging

New Diagnostic for Real-time Measurements of Turbulent Mixing

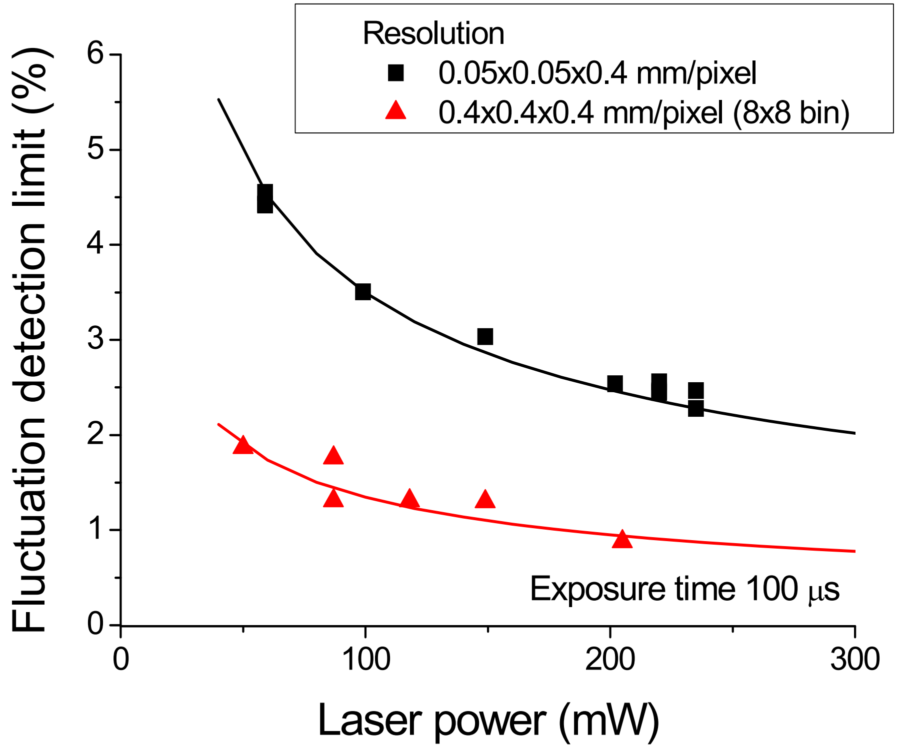
- ***Problem: Use of pulsed lasers limits temporal resolution of tracer-based PLIF***
- Strategy: Use CW laser at 266 nm and toluene (high ϕ) tracer for CW-LIF/PLIF
- CW-LIF/PLIF would offer useful diagnostic for turbulent/fluctuating flows
  - Turbulent mixing of injected fuel streams
  - Studies of jet noise
- Apply CW PLIF to a toluene-seeded, steady N_2 jet to study fluctuation detection limits
  - CW UV light @ 266nm from cavity doubling of commercial 532 nm lasers (5-20W)
  - LIF signal imaged with intensified CCD camera



5. CW PLIF for High-Frame-Rate Imaging

CW PLIF Detection Limits for 266nm Excitation of Toluene

- What is the minimum detectable fluctuation in χ_i?

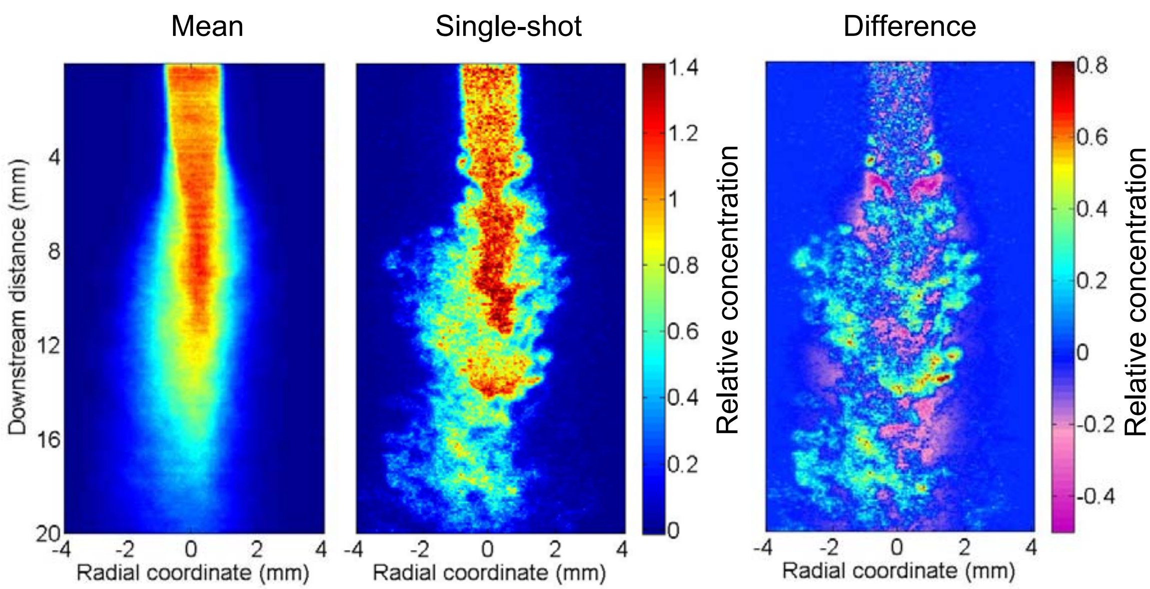


Cheung 2011

- Data consistent with shot-noise detection limit as SNR $\propto$(signal)$^{1/2}$
- Mixture fraction fluctuations < 1% can be detected with 100 μs resolution!
  - 10 kHz frame rate equivalent at each 0.4x0.4x0.4mm pixel

5. CW PLIF for High-Frame-Rate Imaging

CW PLIF Imaging of Mixing in Turbulent Jet: First Demonstrations



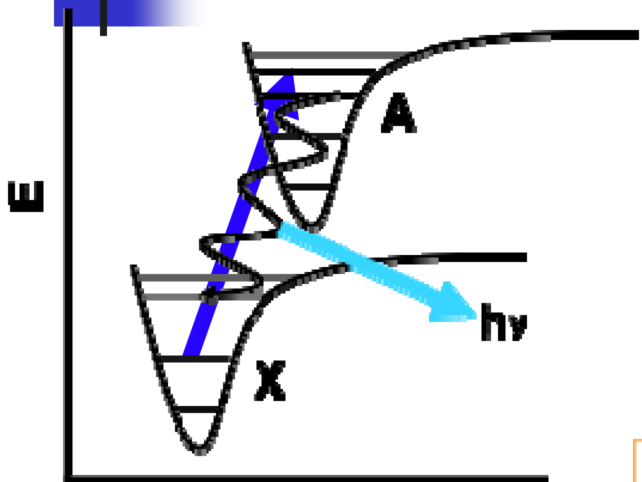
10 μs exposure time
(100 kHz frame rate equivalent)
200 mW laser power
0.05x0.05x0.4 mm/pixel

- N_2 jet seeded with 4% toluene (Re = 10700) in N_2 coflow
- Single-shot images of $X_{mixture}$ show time-varying features of mixing

The Future:

- Improve laser intensity with higher power source, beam homogenizer
- Demonstrate high-speed imaging

6. Toluene PLIF for T Imaging: (1-camera)



Planar Laser-Induced Fluorescence

$$S_f = \frac{E}{h\nu} n\sigma(\lambda,T)\phi(\lambda,T,p_i)\eta$$

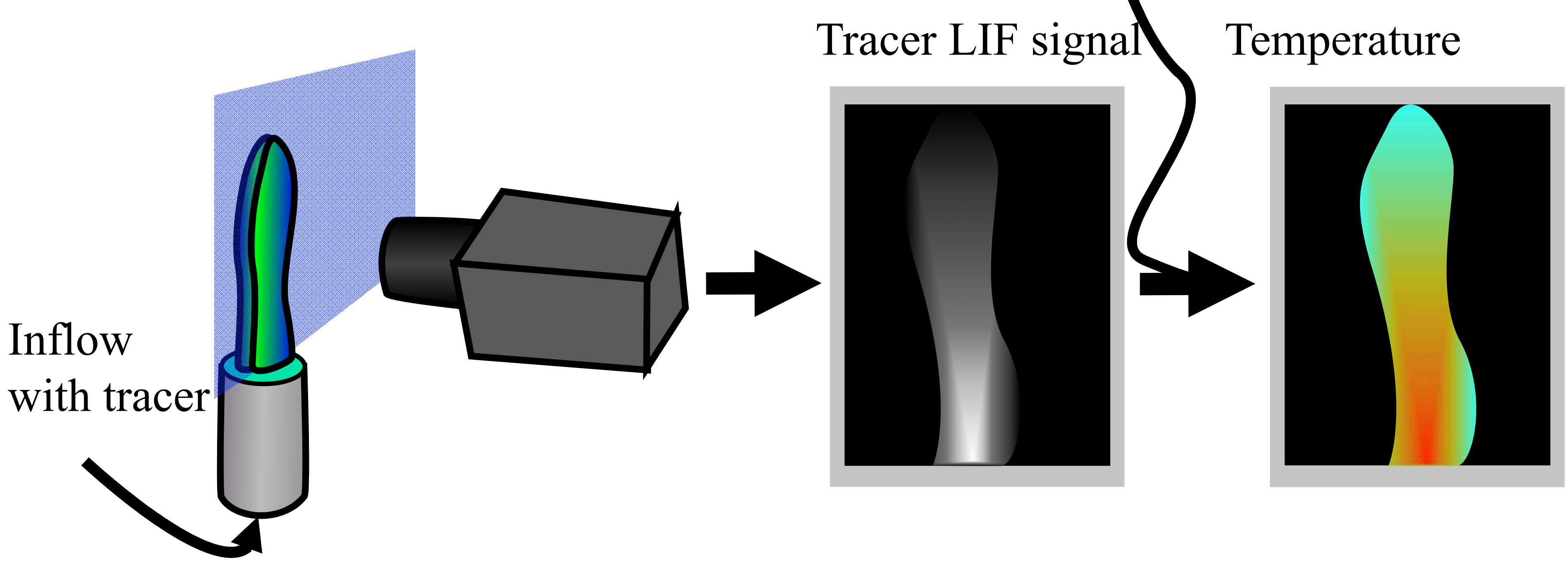
LIF Signal

Incident Photons

Photons Absorbed

Fluorescence Quantum Yield

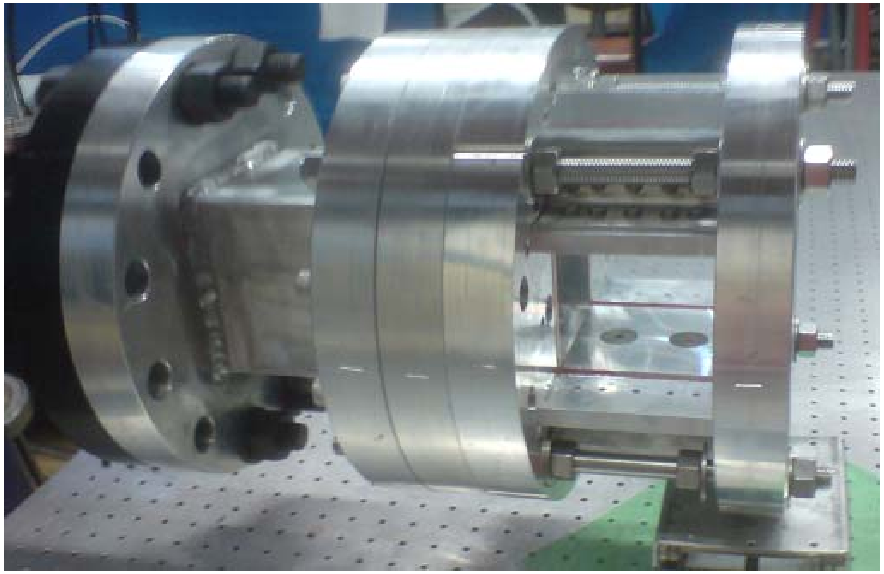
Collection Efficiency



6. Toluene PLIF for T Imaging (1-camera)

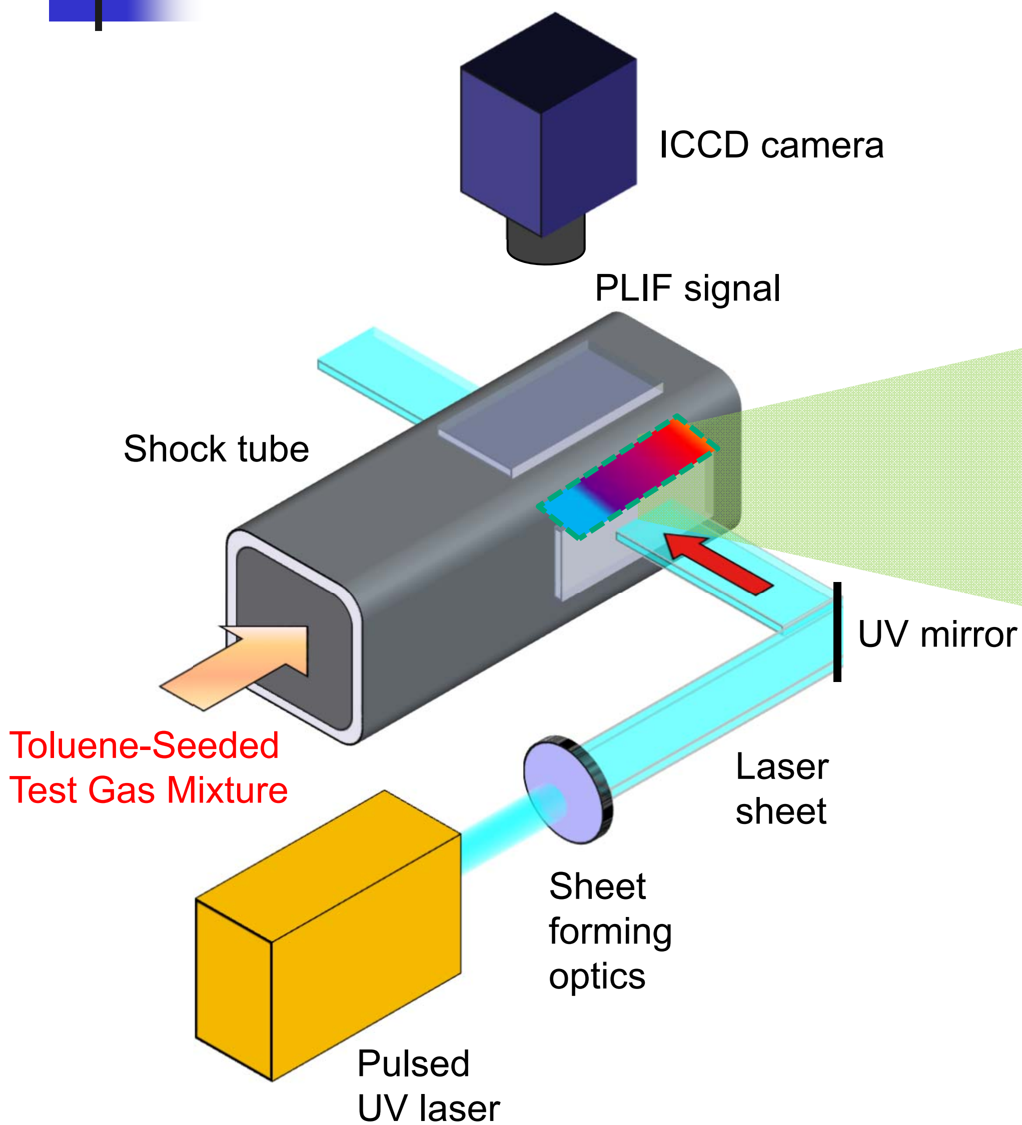
- Critical need for accurate targets to validate CFD simulations of shock/boundary layer interactions
  ➡ PLIF Imaging in a Shock Tube
- Development of new high-sensitivity temperature measurement strategy for imaging
  ➡ Toluene-Based PLIF Temperature Measurement
- Shock tube viewing section enables imaging of reflected shock wave/boundary layer interaction

Four-Window Square Endwall Viewing Section: Stanford Shock Tube

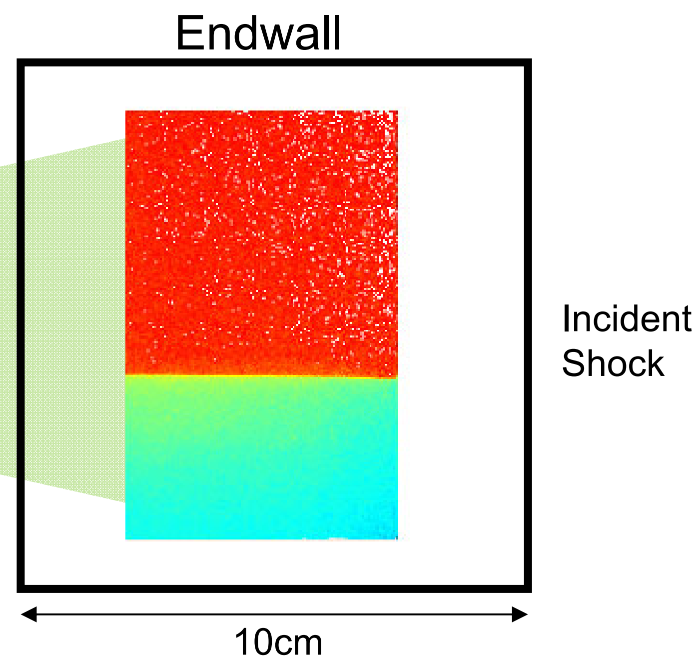


6. Toluene PLIF for T Imaging (1-camera)

PLIF of Incident Shock Wave Arrival



Camera PLIF Image



Shock Flow Conditions:

T_1=296K, T_2=438K,

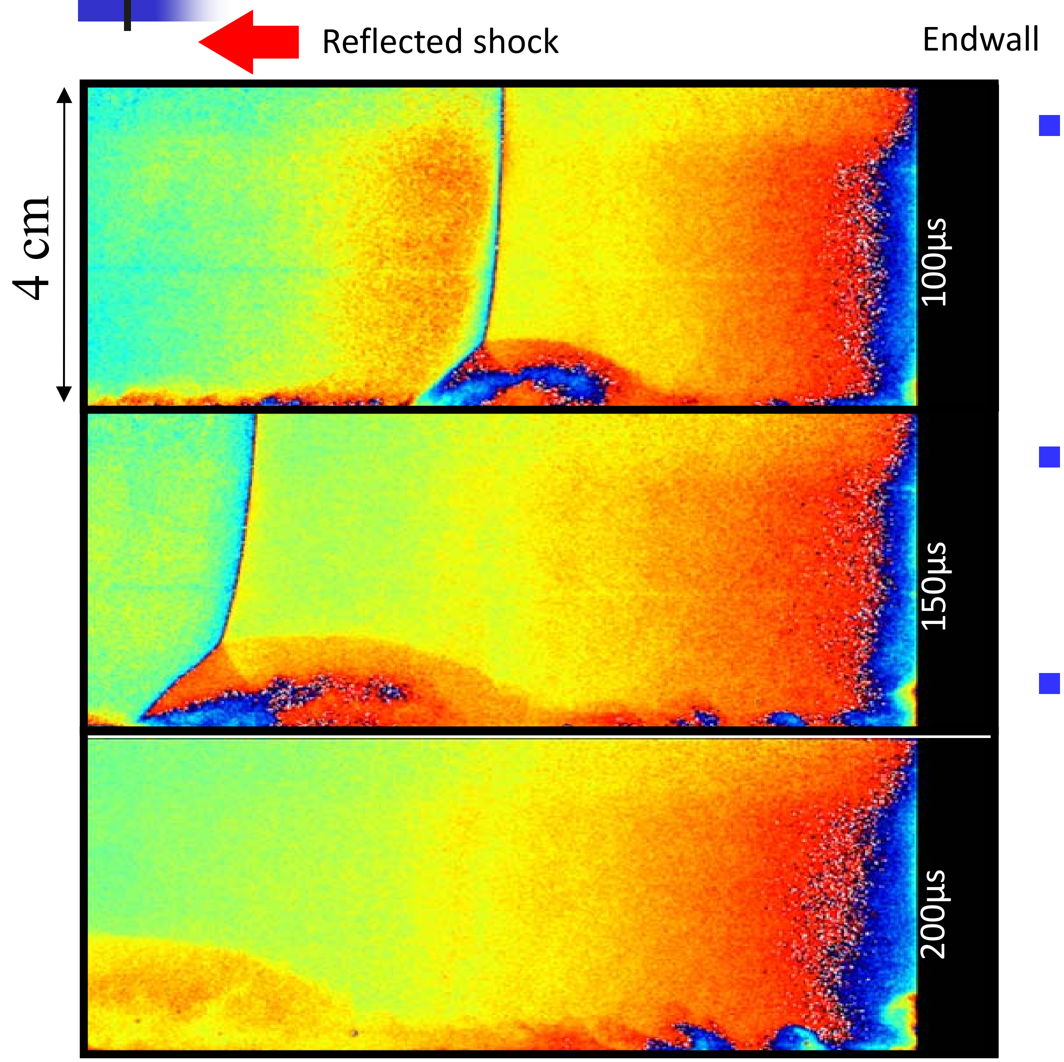
P_1=44torr, P_2=0.24atm,

X_f=7%, Incident V_s=605m/s

Yoo 2011

6. Toluene PLIF for T Imaging (1-camera)

Shock Wave/BL Interaction: Reflected Shock Bifurcation Time Sequence



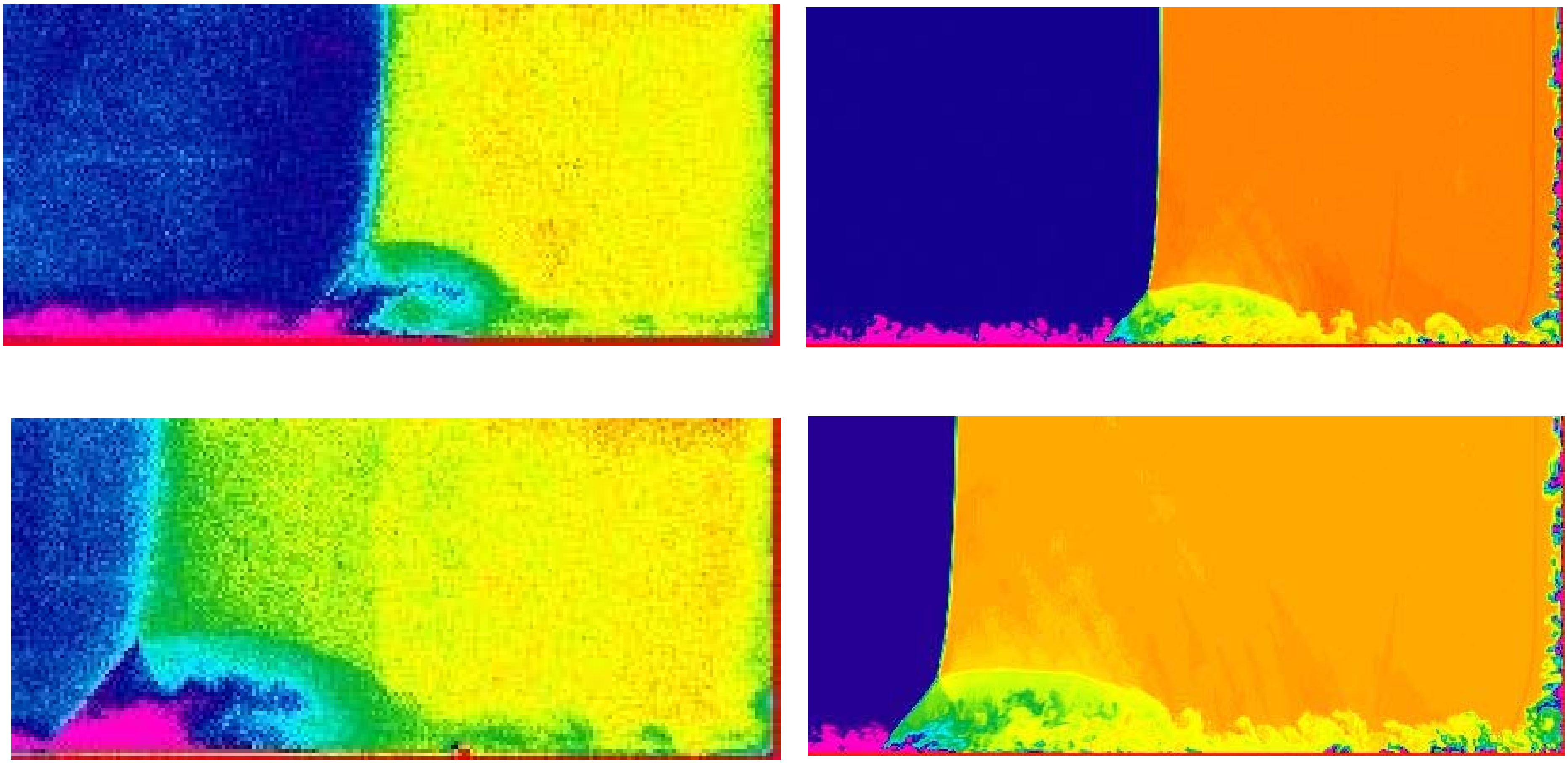
- First toluene PLIF images of shock bifurcation
  - Interaction of reflected shock wave with boundary layer
- Toluene provides sensitive data for ***temperature*** and ***flow structure*** for CFD validation
- Opportunity to apply to other shock/boundary layer flowfields

Shock Flow Conditions:
T_1=296K, T_2=498K, T_5=696K
P_1=32torr, P_2=0.25atm, P_5=1.05atm
X_f=8% Tol/N_2 Incident V_s=710m/s

6. Toluene PLIF for T Imaging (1-camera)

PLIF Signal Comparison with CFD Simulation

Experiment | Simulation (Charles)



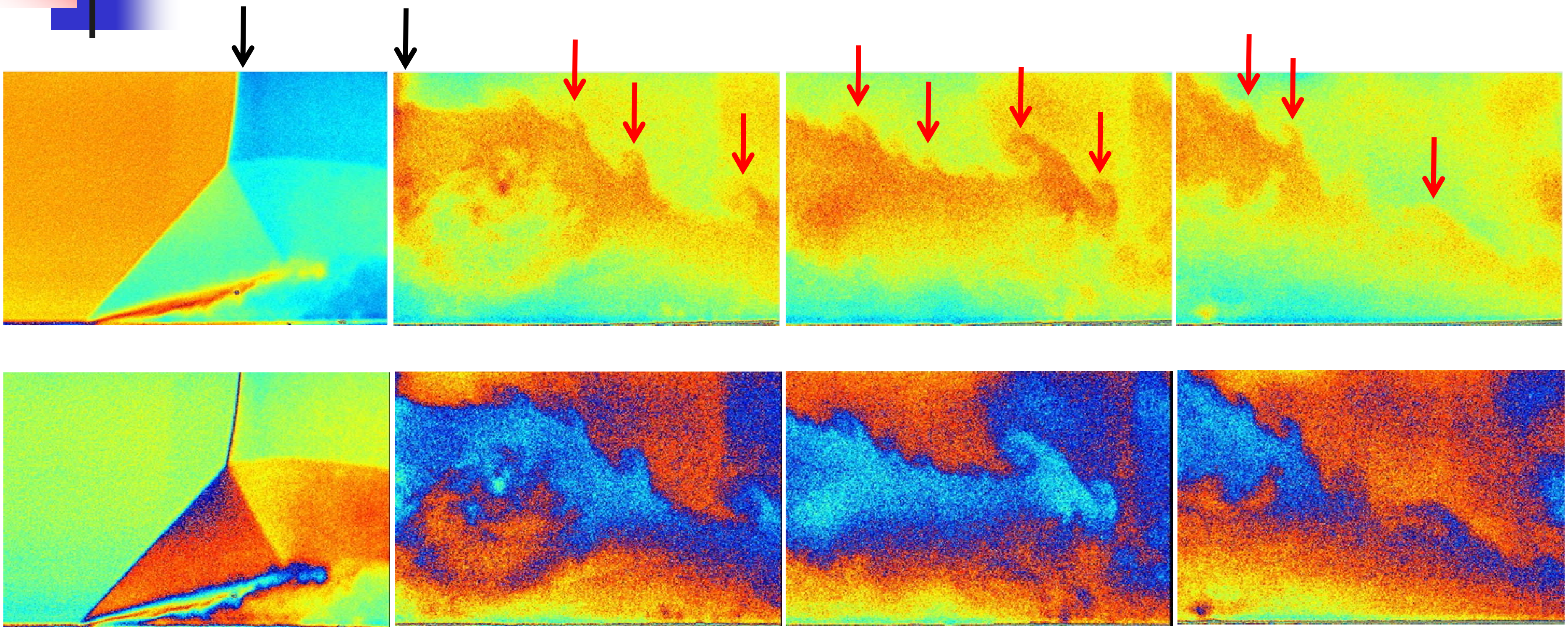
Shock Flow Conditions:

T_1=296K, T_2=498K, T_5=696K

P_1=32torr, P_2=0.25atm, P_5=1.05atm X_f=8%Tol/N_2 Inc. V_s=710m/s

6. Toluene PLIF for Temperature Imaging

Shock Wave/BL Interaction



T=0 μs T=40 μs T=80 μs T=120 μs

- Two different color renditions
- Structure formation revealed

Shock data

P_1 = 21 torr $P_2 \approx 0.143$ atm $P_5 \approx 0.517$ atm

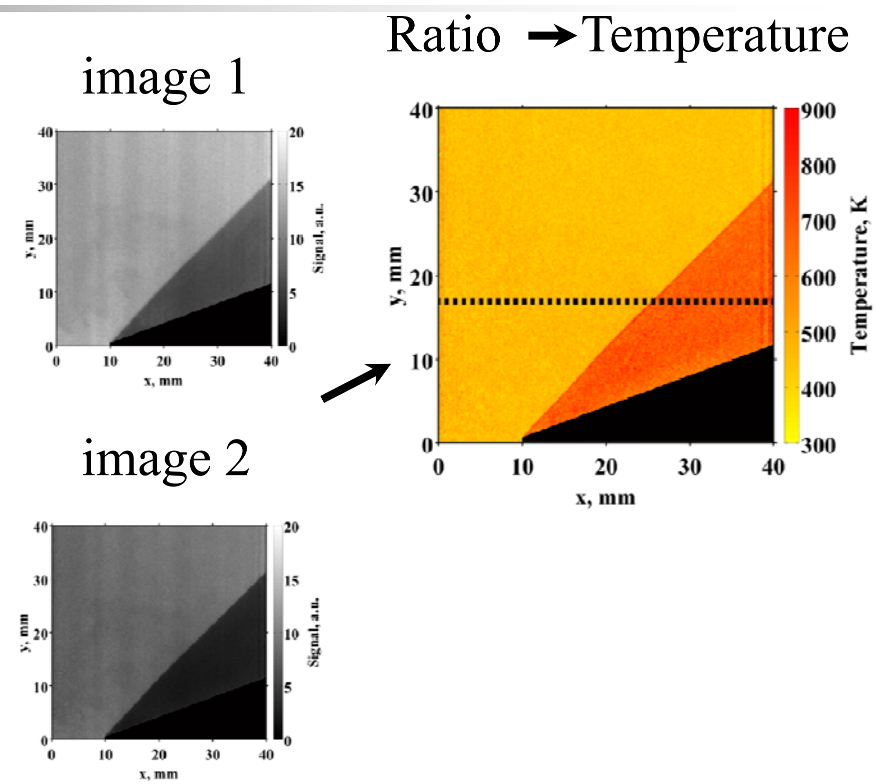
$T_2 \approx 521$K $T_5 \approx 772$K

$V_s \approx 737$ m/s

0.6%Toluene/N_2

7. Toluene PLIF for T Imaging (2-camera)

- Two cameras simultaneously image different spectral regions of fluorescence spectrum
- Select target species or tracer based upon conditions and quantity of interest (e.g., T or x_{O2})
- e.g., toluene, 3-pentanone, acetone



7. Toluene PLIF for T Imaging (2-camera)

- Two cameras simultaneously image different spectral regions of fluorescence spectrum
- Select target species or tracer based upon conditions and quantity of interest (e.g., T or X_{O2})
- e.g., toluene, 3-pentanone, acetone
- With understanding of photophysics of fluorescing species, physical quantities (e.g., T) can be inferred from ratio of images
- Allows for measure of quantity independent of tracer number density

image 1

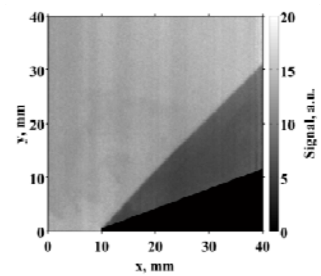
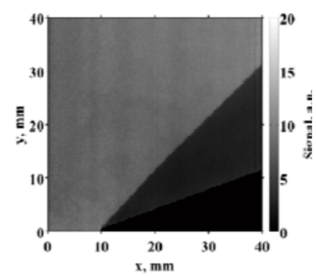
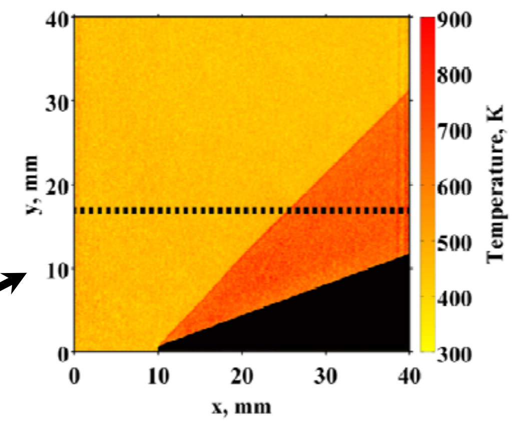
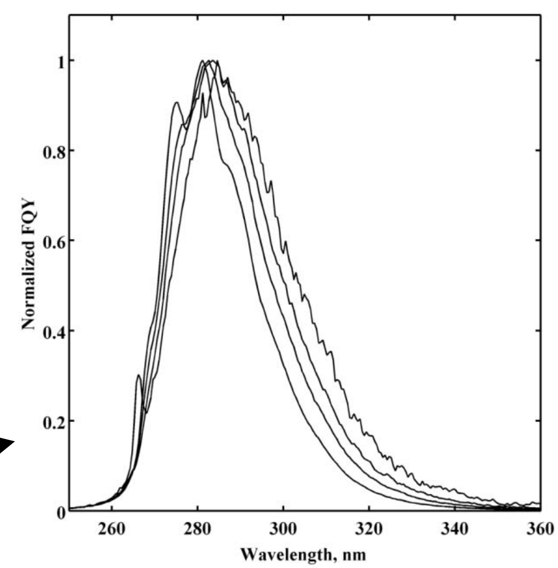


image 2



Ratio → Temperature

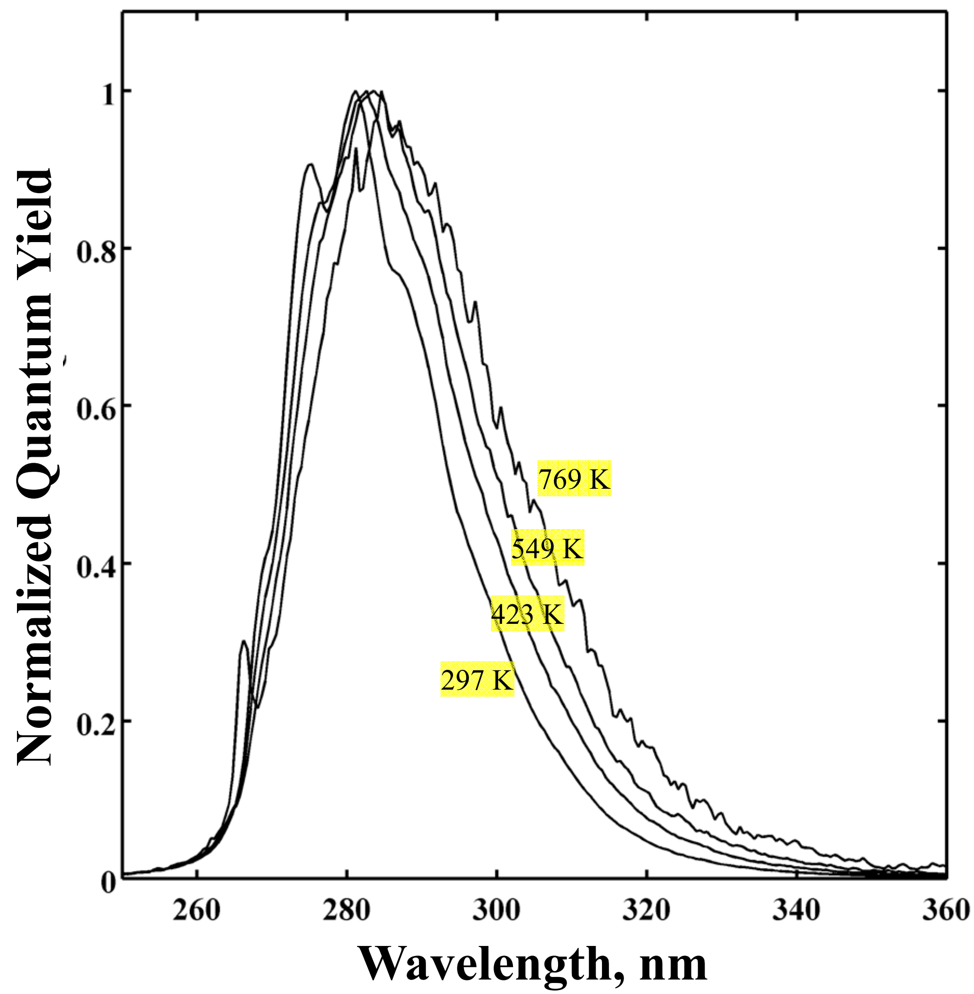




7. Toluene PLIF for T Imaging (2-camera)

- Toluene fluorescence is function of temperature

$$S_f = \frac{E}{h\nu}\frac{P_i}{RT}\sigma(T)\phi(T,\lambda)\eta$$



From Koban, Koch, Hanson, Schulz, 2005

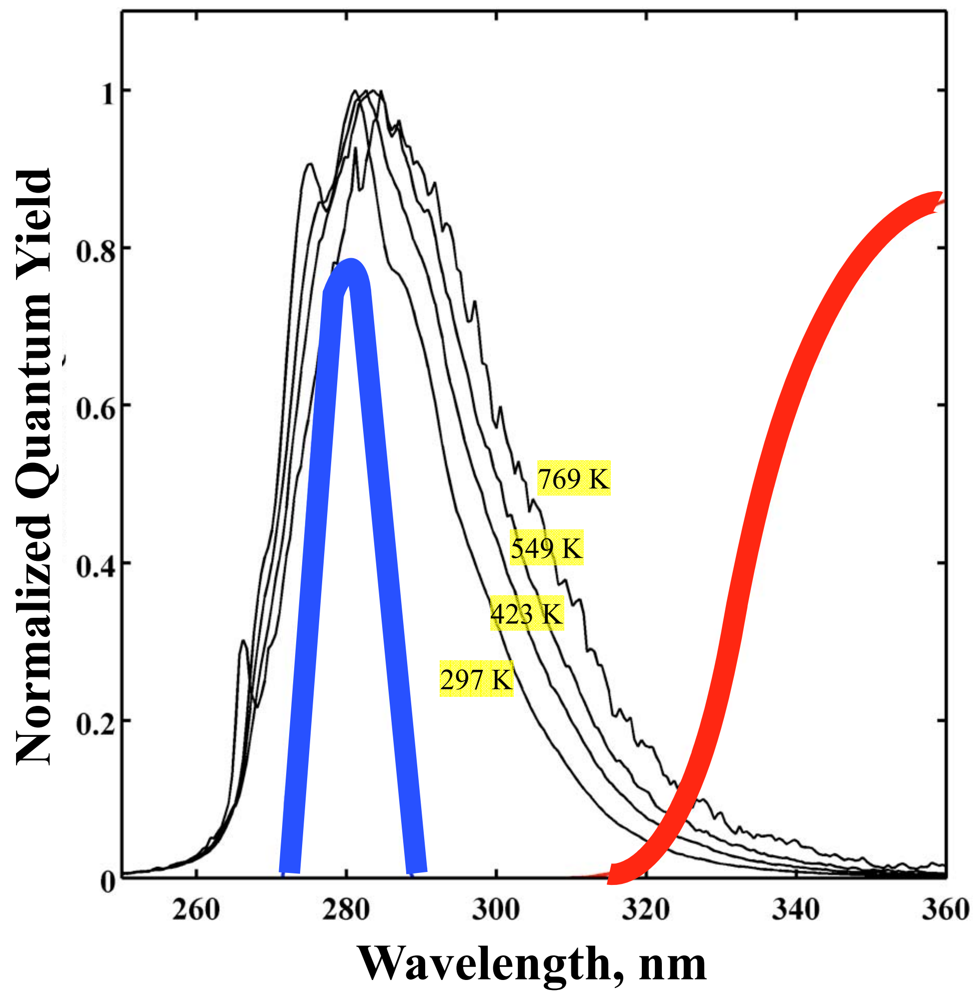
7. Toluene PLIF for T Imaging (2-camera)

- Toluene fluorescence is function of temperature

$$S_f = \frac{E}{h\nu}\frac{P_i}{RT}\sigma(T)\phi(T,\lambda)\eta$$

but depends on filter, F(λ), thus

$$S_f = \frac{E}{h\nu} n\sigma(T)\eta\int\phi(\lambda,T)F(\lambda)$$



From Koban, Koch, Hanson, Schulz, 2005

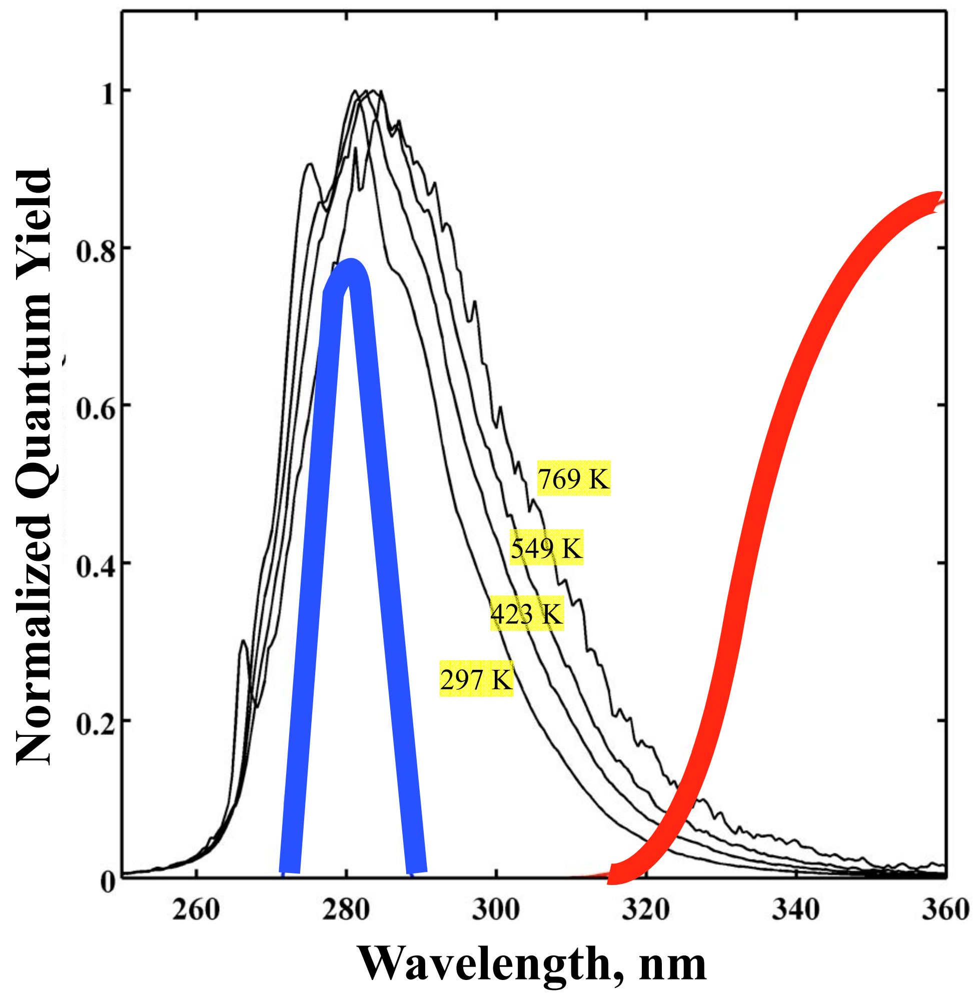
7. Toluene PLIF for T Imaging (2-camera)

- Toluene fluorescence is function of temperature

$$S_f = \frac{E}{h\nu}\frac{P_i}{RT}\sigma(T)\phi(T,\lambda)\eta$$

$$S_f = \frac{E}{h\nu}n\sigma(T)\eta\int\phi(\lambda,T)F(\lambda)$$

$$\frac{S_1}{S_2} = \frac{\int\phi(\lambda,T)\underline{F_1(\lambda)}}{\int\phi(\lambda,T)\underline{F_2(\lambda)}}$$



From Koban, Koch, Hanson, Schulz, 2005

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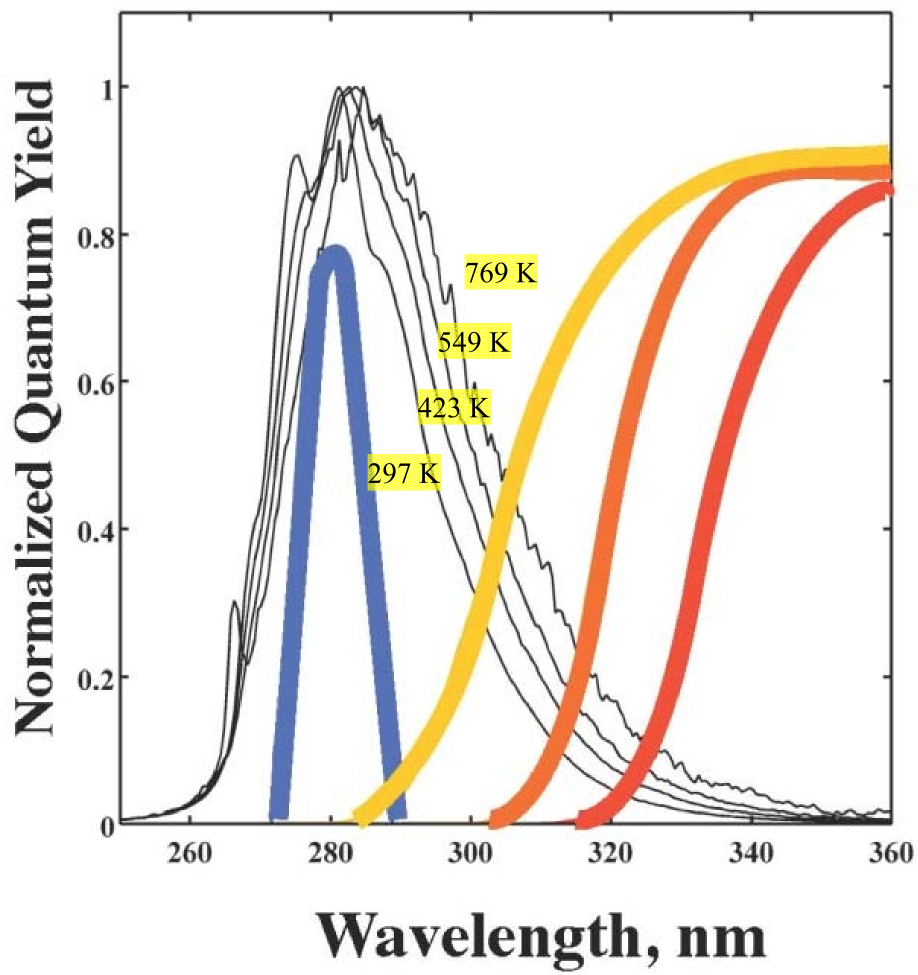

- Three sets of filters examined

From Koban, Koch, Hanson, Schulz, 2005

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- Toluene fluorescence is function of temperature

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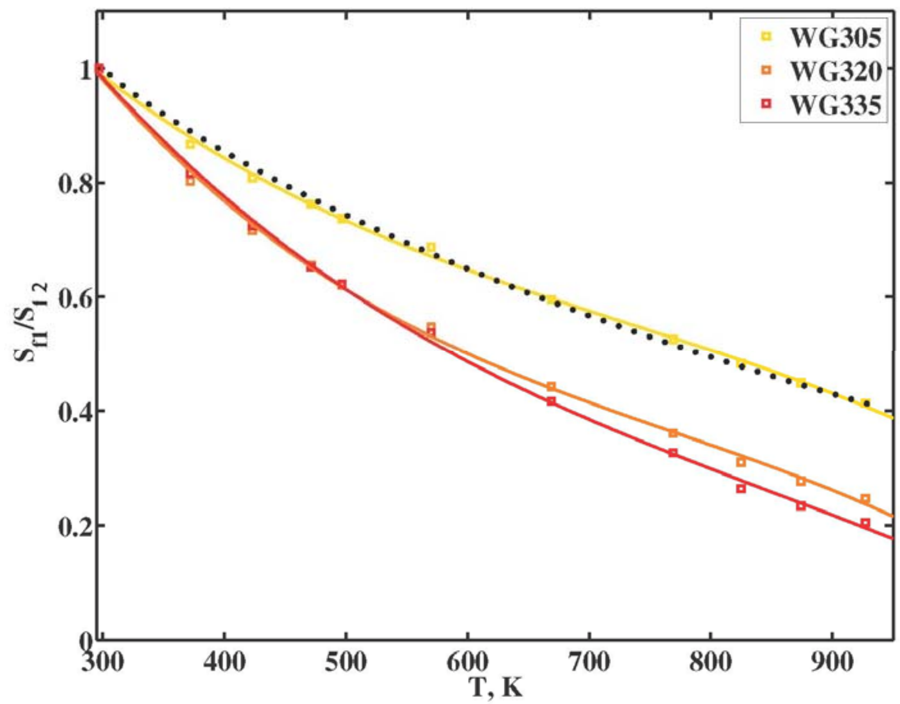
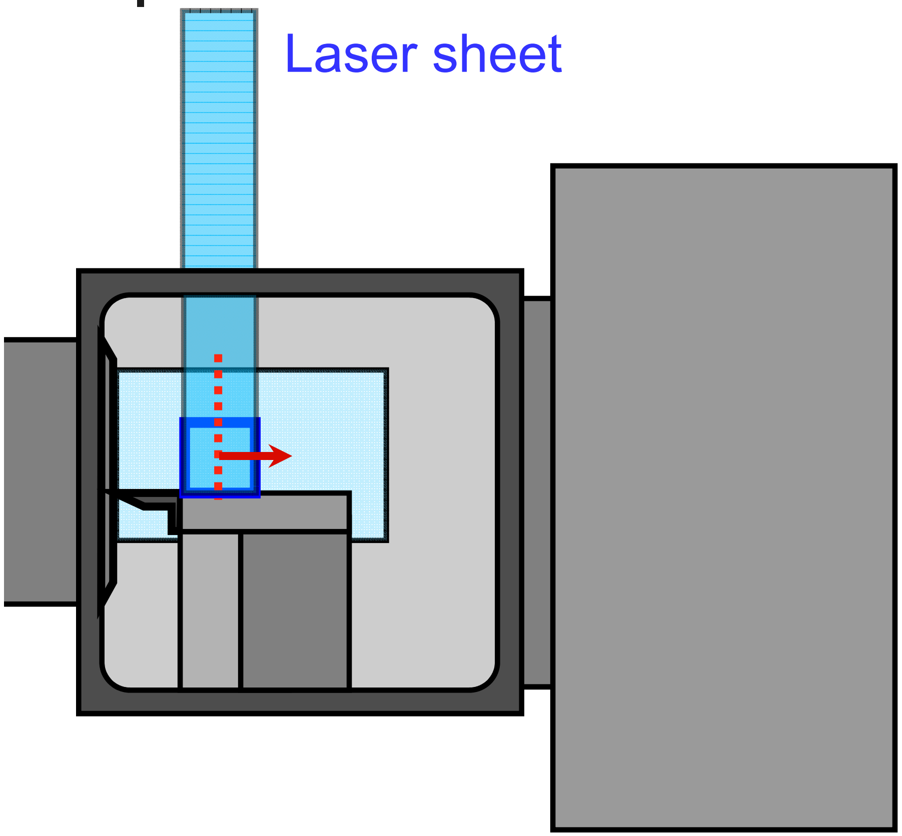


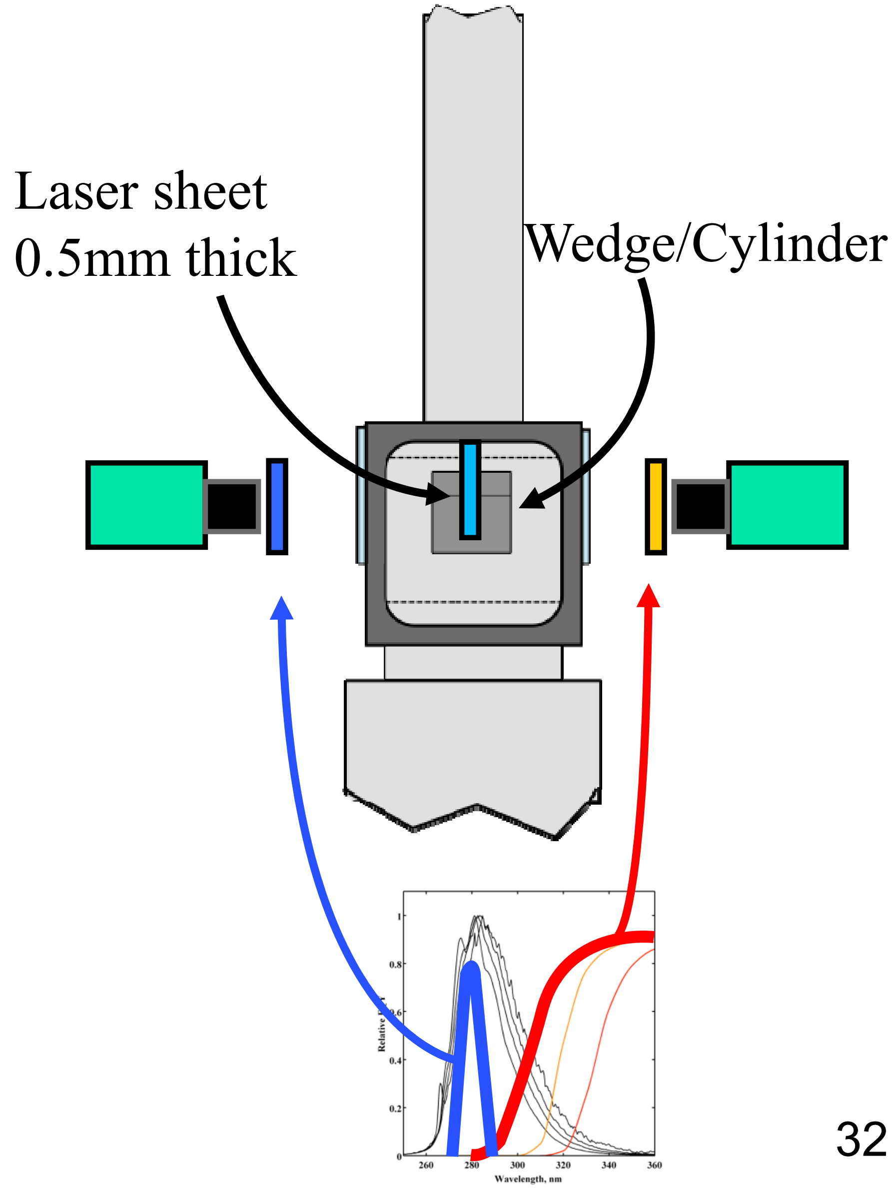
Next: 3 demonstrations of 2-camera T imaging

From Koban, Koch, Hanson, Schulz, 2005

7. Toluene PLIF for T Imaging (2-camera)

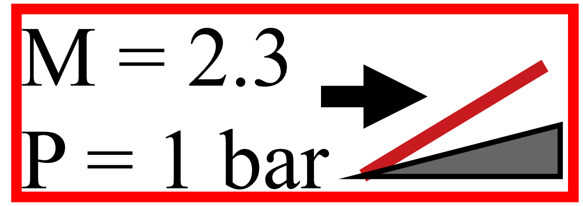
Experimental setup

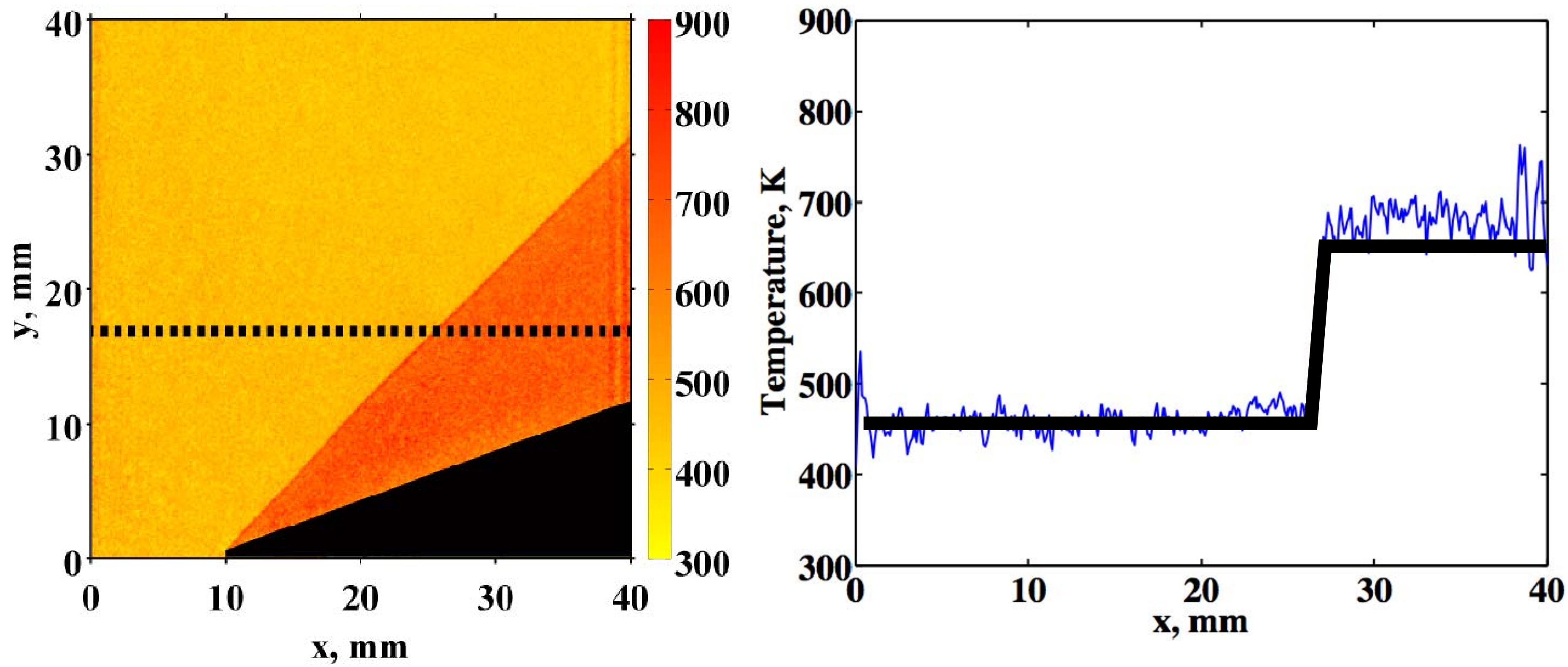




7. Toluene PLIF for T Imaging (2-camera)

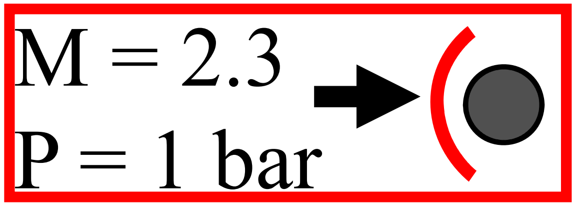
Wedge Flow: Temperature Imaging

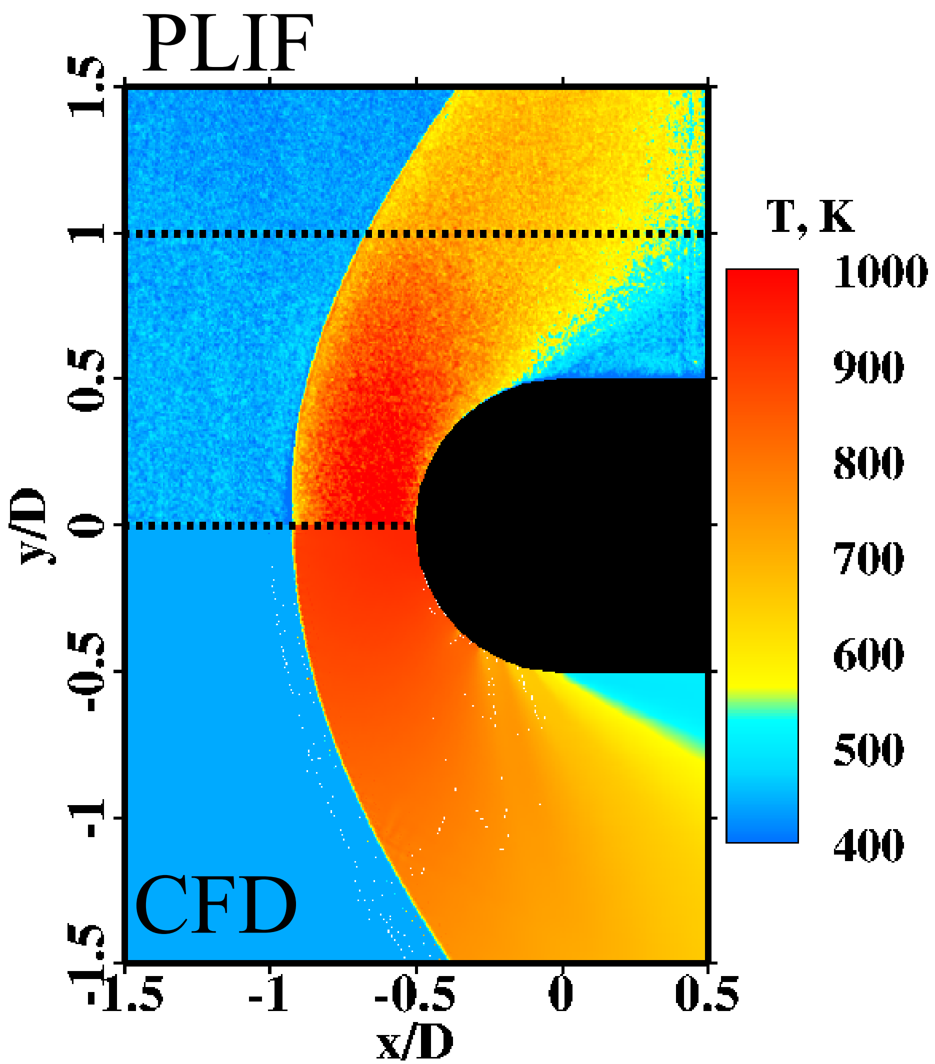




7. Toluene PLIF for T Imaging (2-camera)

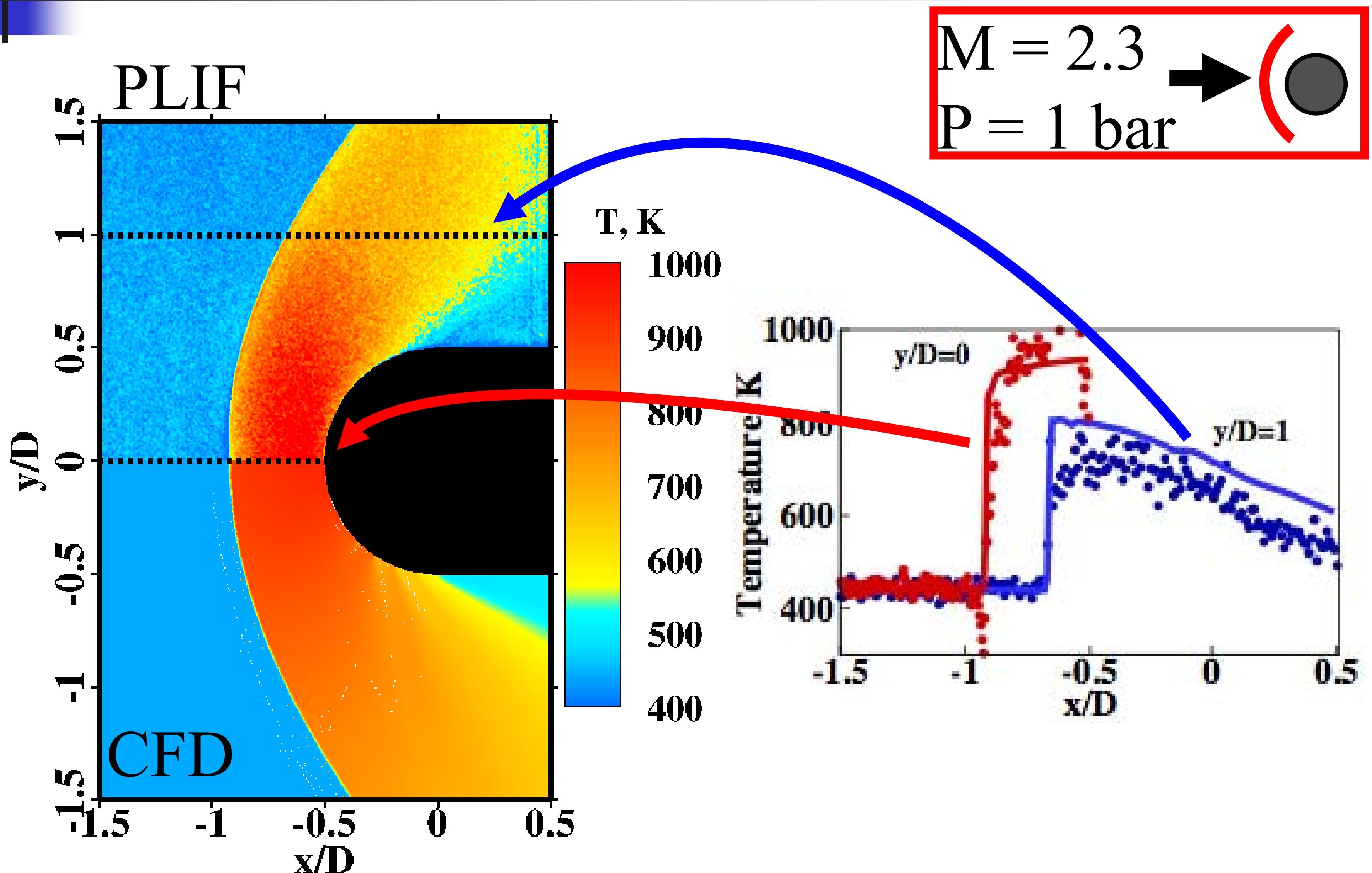
Cylinder Flow: Temperature Imaging





7. Toluene PLIF for T Imaging (2-camera)

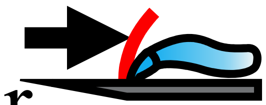
Cylinder Flow: Temperature Imaging



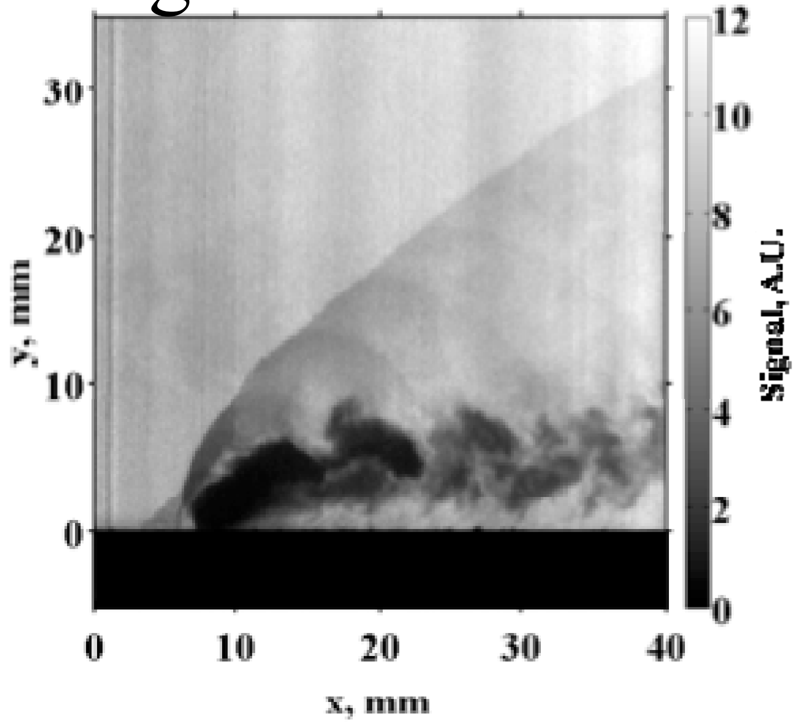
7. Toluene PLIF for T Imaging (2-camera)

Jet in Crossflow: Temperature Imaging

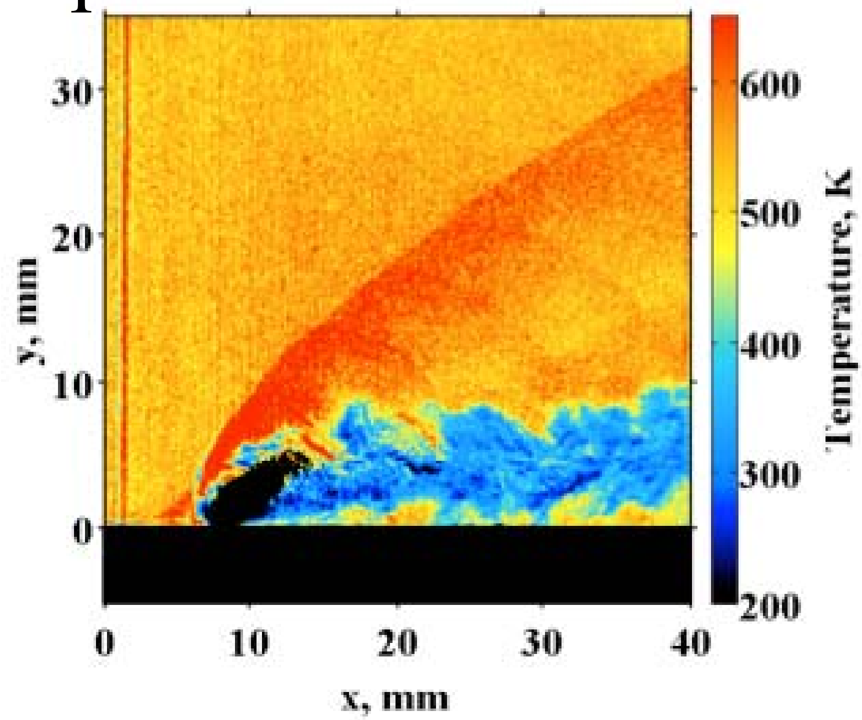
M = 2.3
P = 1 bar



Raw Signal



Temperature



9. The Future for PLIF Imaging in Complex Flows

- Applications
  - Non-ideal effects in shock tubes (shock/boundary layer)
  - IC-Engines (EGR, T, radicals, pollutants)
  - SCRAMJETS (mixing, flame structure)
  - Fluid dynamics (mixing, turbulent combustion)
  - Plasma-enhanced combustion (flame structure, species)
- Species
  - Tracers (toluene, ketones, NO)
  - Naturally present (CO_2, UHC, OH, NO)
- Strategies
  - High-speed PLIF
  - Multi-parameter imaging (T, species)
  - IR PLIF

Quantitative Laser Diagnostics for Combustion Chemistry and Propulsion

Closing Comments: The Future

- Use of laser diagnostics will become increasingly routine
- Availability of packaged systems will continue to grow
- Availability and cost of mid-IR TDLAS will improve
- Sensitivity improvements will be found (e.g. CEAS)
- Use of hi-rep PLIF systems will become more common
- New PLIF tracers and techniques employing traces will be found
- Laser diagnostics will play a key and expanding role in future research on combustion

- **The future for laser diagnostics is bright!**
- **Thanks for attending this short course!**
- **Best wishes for your future!**