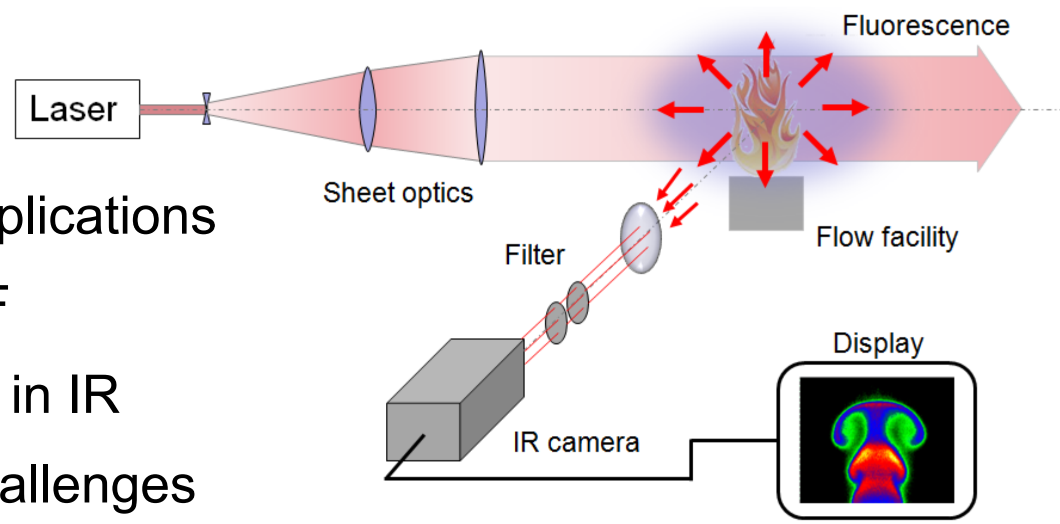
Quantitative Laser Diagnostics for Combustion Chemistry and Propulsion

Lecture 14: Applications of LIF, PLIF of Small Molecules

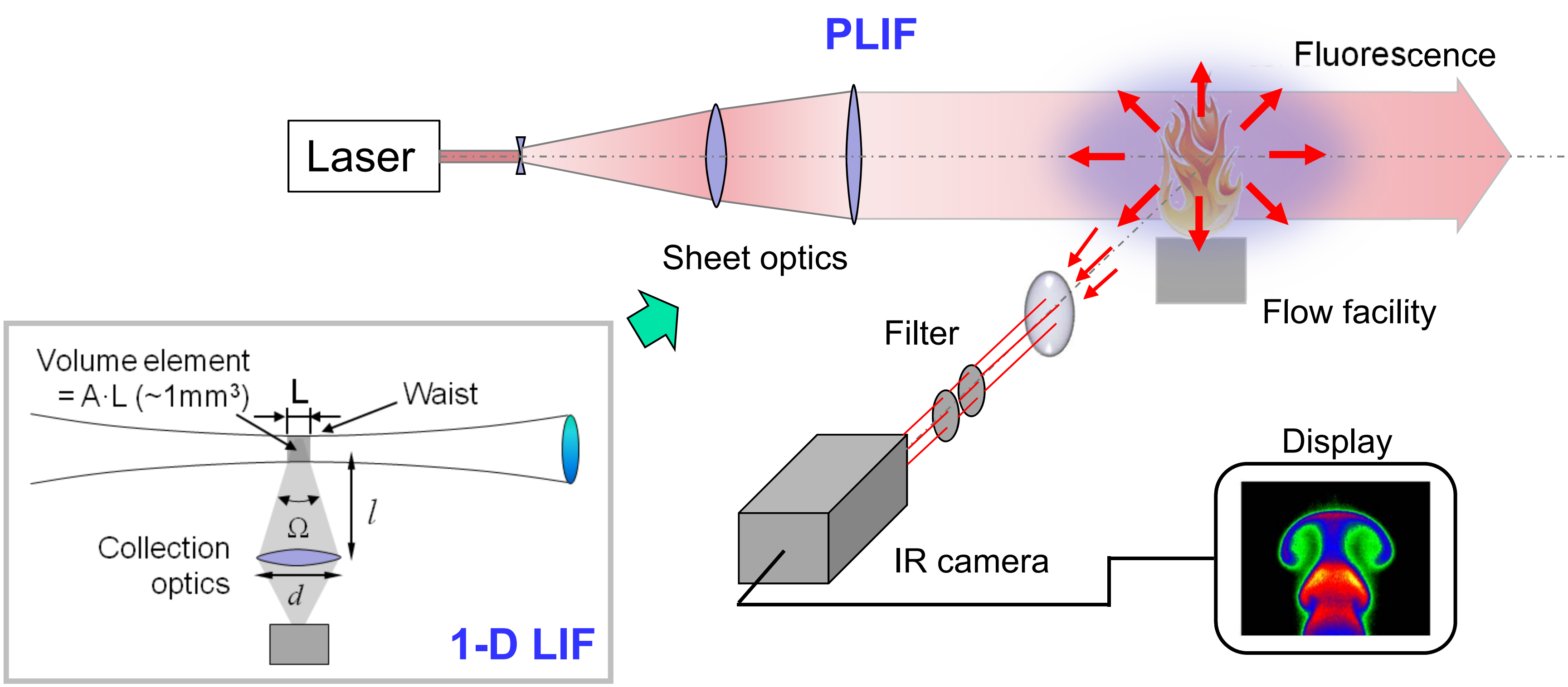
*P*lanar *L*aser *I*nduced *F*luorescence



1. Intro to LIF & PLIF imaging applications
2. Flame applications of OH PLIF
3. PLIF with molecular vibrations in IR
4. Imaging hypersonic flows – challenges
5. Imaging hypersonic flows – PLIF of OH in reacting and non-reacting flows
6. Imaging hypersonic flows – T and dual species

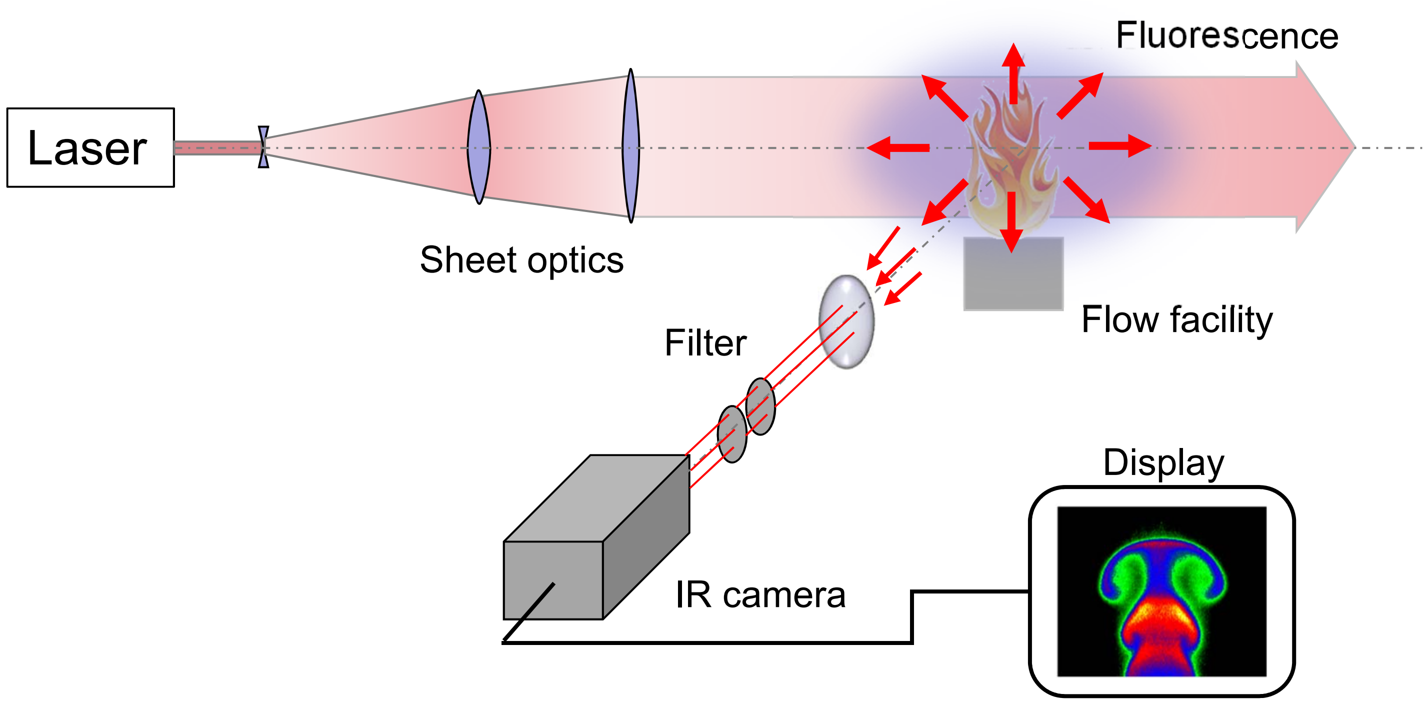
1. Introduction to LIF & PLIF Imaging

- *P*lanar *L*aser *I*nduced *F*luorescence (PLIF): A two-dimensional image can be acquired using LIF by
  - Using a 2-D detector array (i.e. digital camera)
  - Expanding the excitation laser beam into a sheet



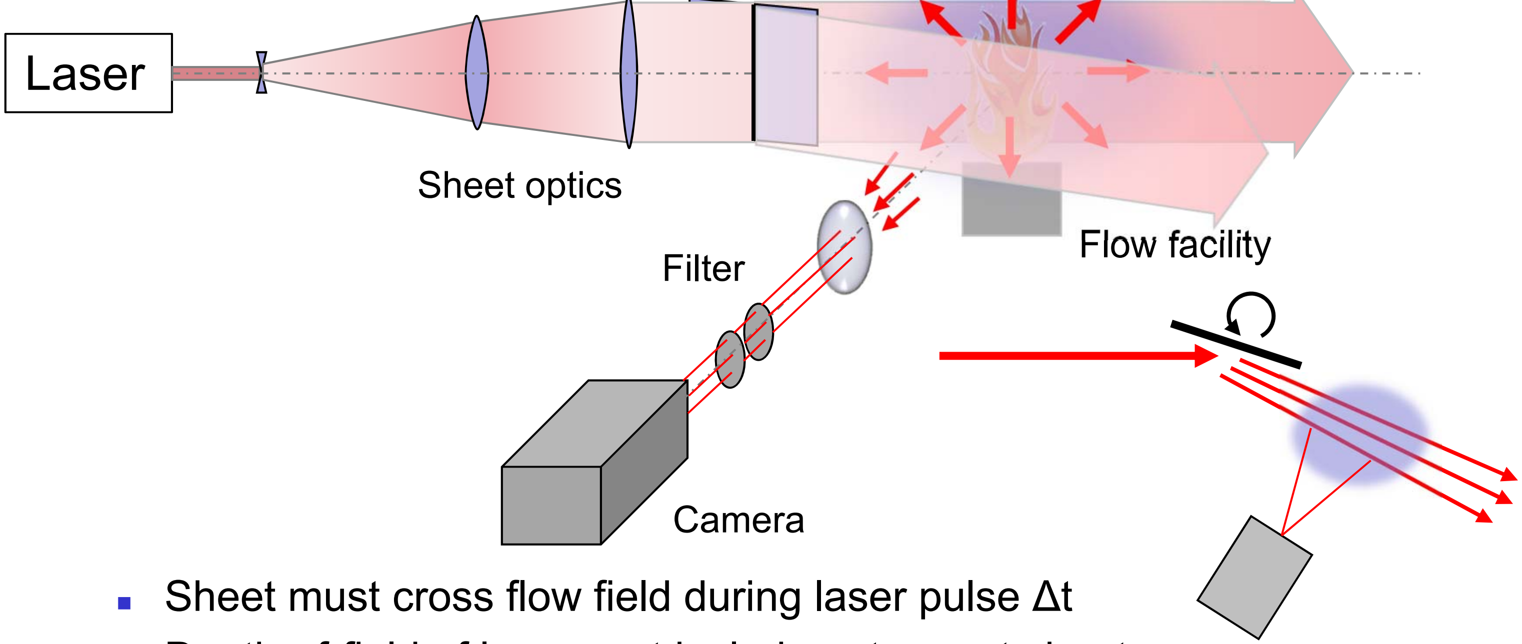
1. Introduction to LIF & PLIF Imaging

- Pulsed lasers are used to achieve single-shot imaging
- Shot excitation pulse effectively freezes the flow field
- Can suffer from lower SNR than 1-D LIF because the laser energy is spread out over a much larger area
- May use averaged measurements for improved SNR with either CW or pulsed laser excitation for steady systems



1. Introduction to LIF & PLIF: 3D-PLIF

- 3-D PLIF
  - scan laser sheet



    - Sheet must cross flow field during laser pulse Δt
    - Depth-of-field of lens must include outermost sheets
    - Camera must frame quickly; #sheet/Δt
  - Display methods
    - Orthogonal slices (cube display)
    - Surface rendering
    - Movie

1. Introduction to LIF and PLIF Imaging

Application of LIF to species density

- Species density

Measure n_i [molecules/cc] with LIF using linear excitation

$$S_F\left[\text{photons/s}\right] = n_1^0 \cdot V \cdot I_\nu B_{12} \cdot \frac{A_{21}}{A_{21}+Q_{21}} \cdot \frac{\Omega}{4\pi} \propto n_i \frac{f_{v,J}(T)}{Q}$$

- Assume known: A_{21}, B_{21};

  I_ν, V & Ω are usually measured (i.e., by Rayleigh scattering)

Rayleigh: $P_{\text{scattered}}^{\text{out}}\left[\text{W}\right] = P_{\text{in}}\left[\text{W}\right] nL \frac{\partial\sigma}{\partial\Omega}\Omega$

$$= \left[\frac{P_{\text{in}}}{A}\right](nAL)\frac{\partial\sigma}{\partial\Omega}\Omega$$

intensity $I(\nu) = I_\nu \delta\nu$

$$P_{\text{scattered}}^{\text{out}}\left[\text{W}\right] = I_\nu \delta\nu n V \frac{\partial\sigma}{\partial\Omega}\Omega$$

$$= \underbrace{n}_{\text{set in experiment}}\ \underbrace{\delta\nu}_{\text{measure}}\ \underbrace{\frac{\partial\sigma}{\partial\Omega}}_{\text{known}}\left[I_\nu V\Omega\right]$$

Can infer $I_\nu V\Omega$

- Then $S_F \propto C\cdot n_i$, where $C \propto V\Omega f_{v,J}/Q$ is from a calibration point
- For T-varying systems, need to select v and J to give $f_{v,J}/Q$ independent of T

1. Introduction to LIF and PLIF Imaging

Application of LIF to species mole fraction

- Species mole fraction

$$
\begin{aligned}
S_F[\text{photons/s}] &\propto n_i \frac{f_{\mathrm{v},J}(T)}{n\sigma\bar{c}} \\
&= X_i \frac{f_{\mathrm{v},J}(T)}{\sigma\sqrt{T}} \\
&\approx C \cdot X_i
\end{aligned}
$$

- $Q = n\sigma\bar{c}$, $\bar{c}$ = mean molecular speed
- C is obtained by calibration
- Requires selection of v and J to give $\dfrac{f_{\mathrm{v},J}}{\sigma\sqrt{T}} \neq f(T)$

1. Introduction to LIF and PLIF Imaging

Application of LIF to temperature

- Temperature
  - Strategy 1: Single-line method

$$S_F \propto X_i \frac{f_{v,J}(T)}{\sigma\sqrt{T}}$$

    - Use a tracer with fixed X_i
    - Select v and J for large T dependence of $\frac{f_{v,J}}{\sigma\sqrt{T}}$

  - Strategy 2

$$\frac{S_F(1)}{S_F(2)} = \frac{\left[n_i \frac{f_{v,J}(T)}{Q}\right]_1}{\left[n_i \frac{f_{v,J}(T)}{Q}\right]_2} \approx \frac{f_{v,J}(T)_1}{f_{v,J}(T)_2} = F(T)$$

    - Select λ_1 and λ_2 to probe states with strong T-dependence for $f_{v,J}(T)_1 / f_{v,J}(T)_2$

1. Introduction to LIF and PLIF Imaging
30 Years: From Concept to Standard Tool

1982 – 1st PLIF in flames

1984 – 1st PLIF in turbulent flames

1987 – 3D digital flow field mapping with PLIF

1992 – Acetone tracers to visualize flow mixing with PLIF

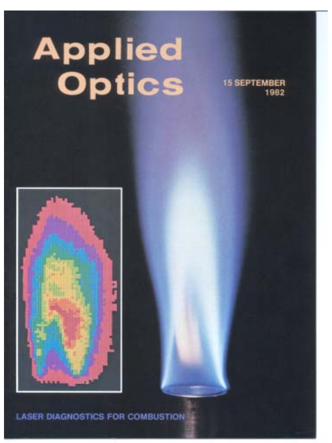
1993 – PLIF investigation of scamjet fuel mixing

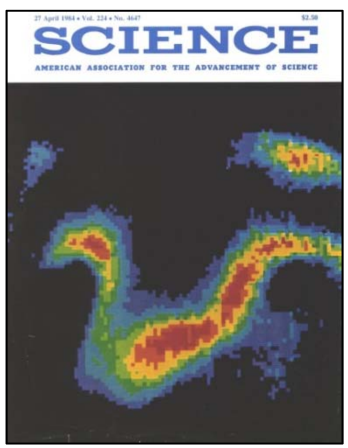
1996 – PLIF imaging of temperature in supersonic jet

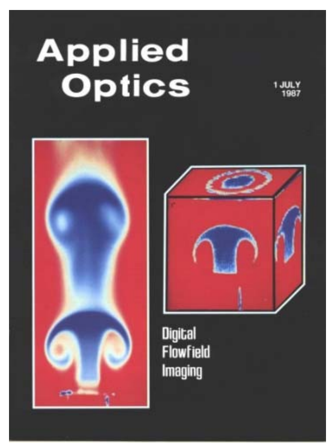
2000-present – Transition of tracer-based PLIF imaging into industrial labs

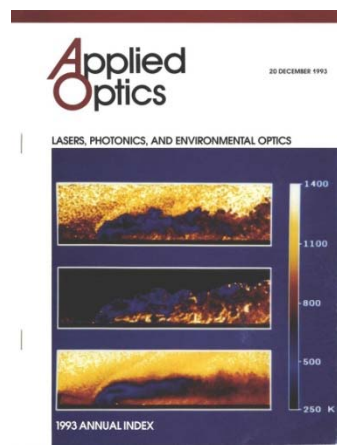
Where is PLIF today:

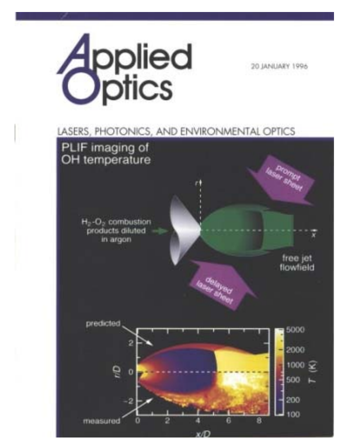
2012 – Use of kHz rate PLIF in practical aeropropulsion problems (e.g., swirl burner)





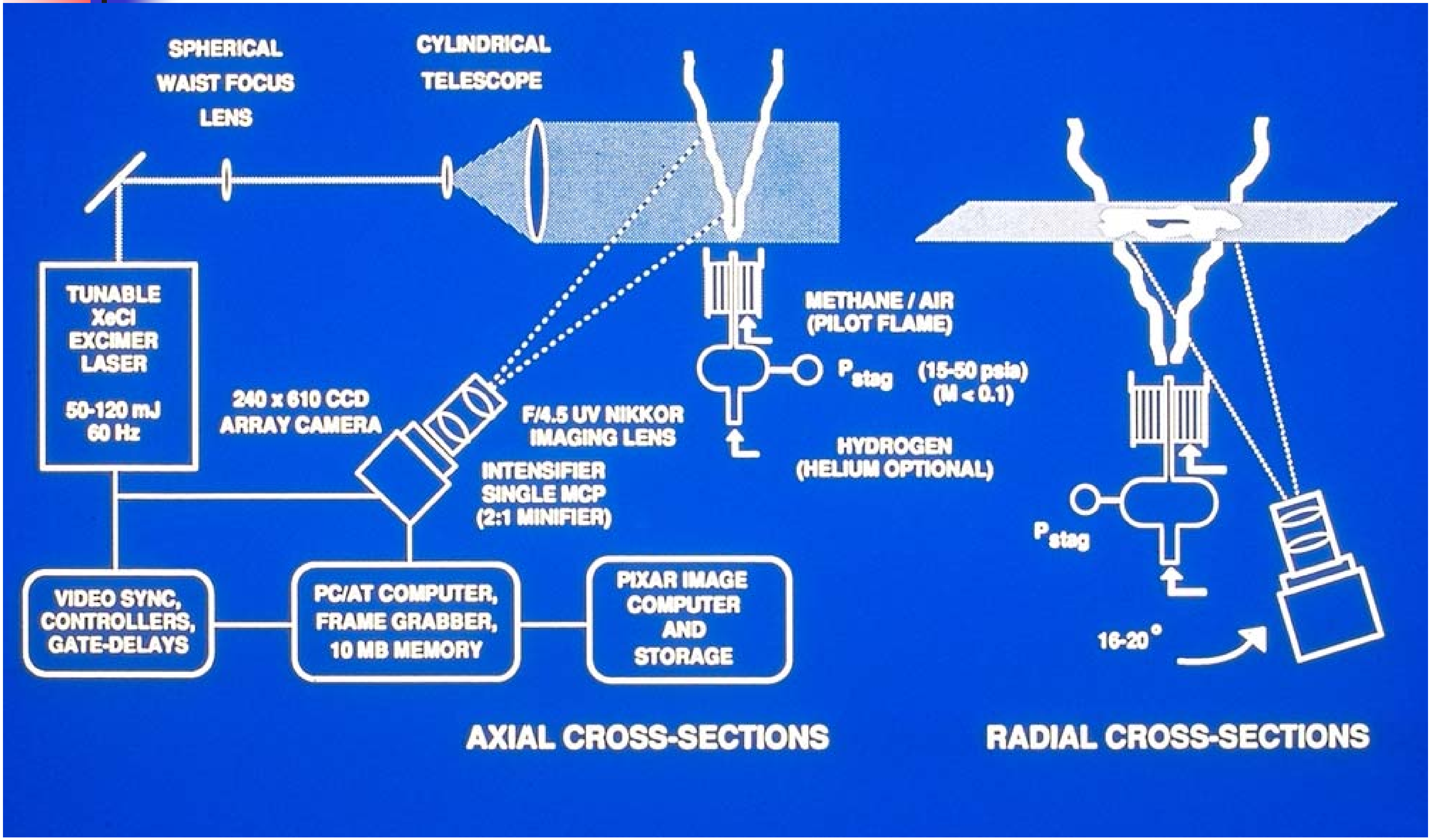






Now some applications of tracer-based PLIF

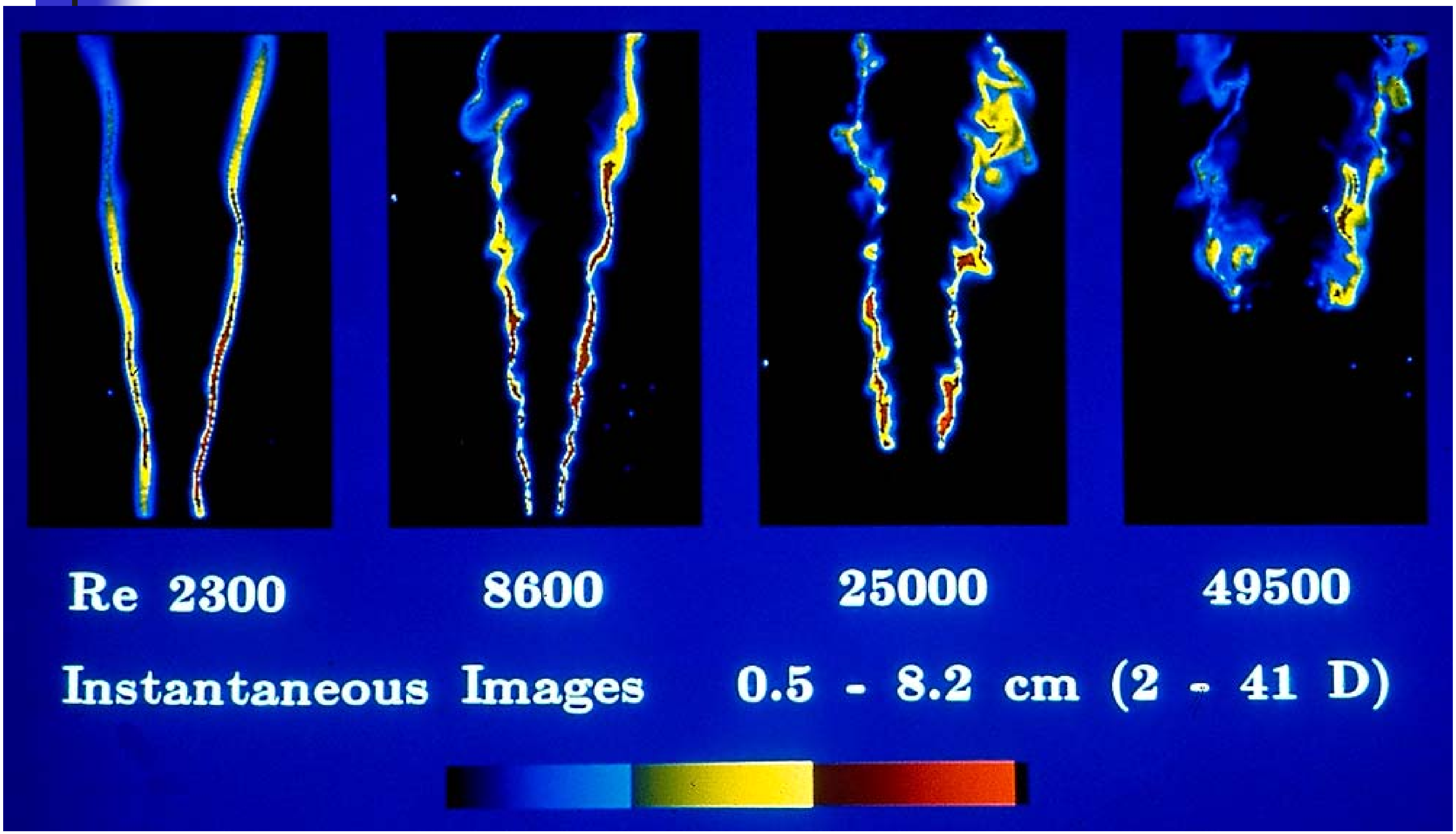
2. Flame Applications for OH PLIF:
A Tool for Turbulent Flame Research



Seitzman et al, 23rd International Symposium on Combustion (1990)

2. Flame Applications for OH PLIF

Flame Structure vs Reynolds Number via OH PLIF

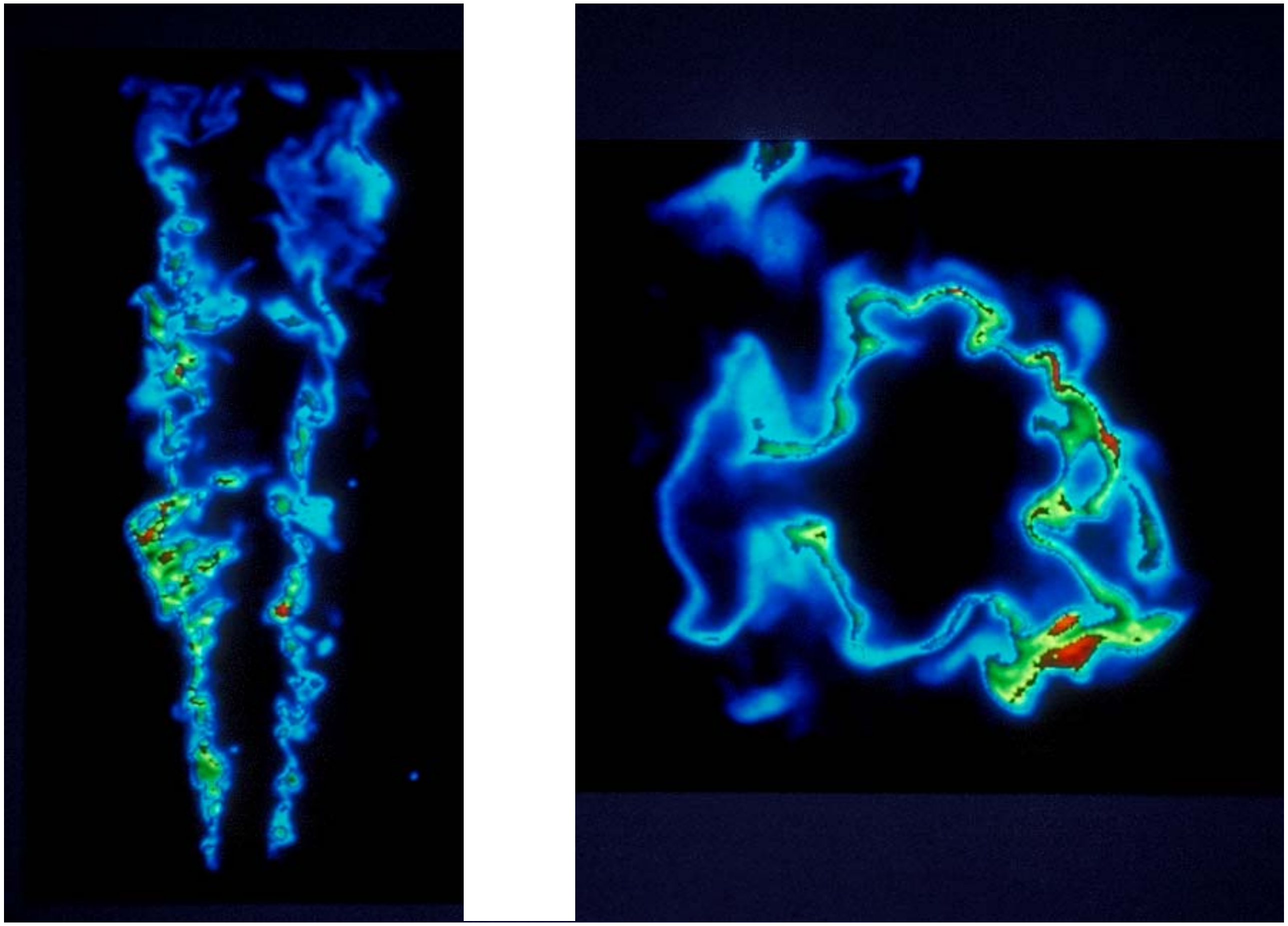


- OH PLIF of a hydrogen diffusion flame in air (2.2mm diameter jet)

2. Flame Applications for OH PLIF

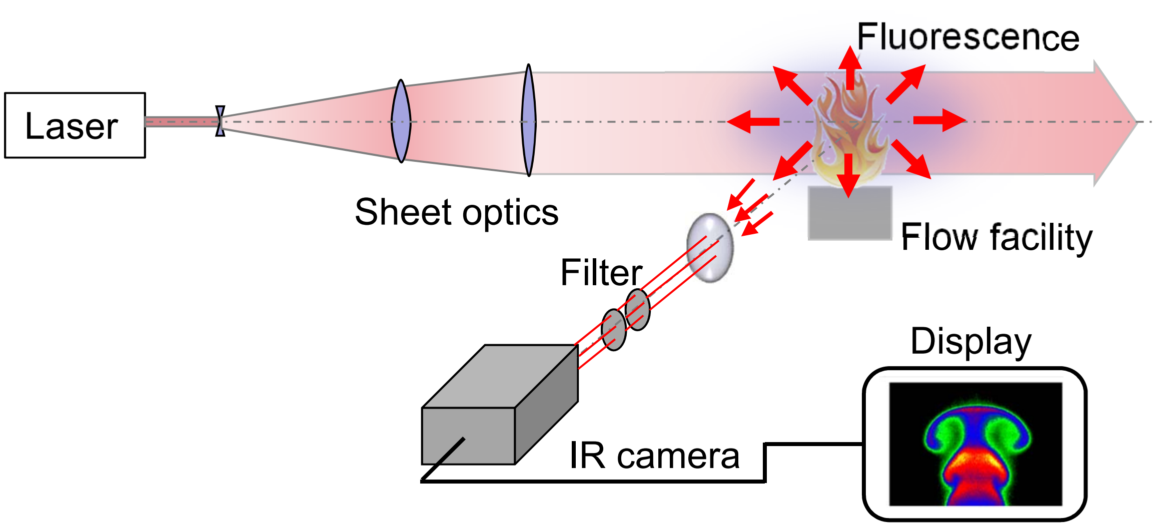
Diffusion Flame Structure using OH PLIF

- H_2/air diffusion flame
- 2.2 mm diameter jet
- Re~24,000

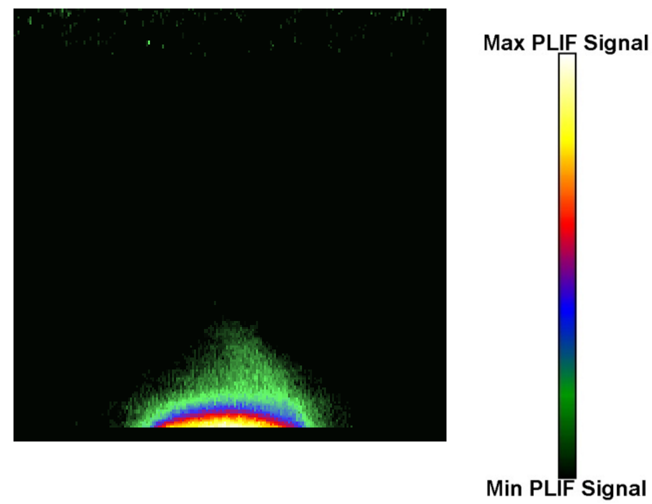


- OH PLIF to visualize flame structure in a plane vs
  1. Axial distance from the nozzle exit
  2. Radial distance from the fuel jet axis

3. PLIF with Molecular Vibrations in IR



Forced CO_2 jet



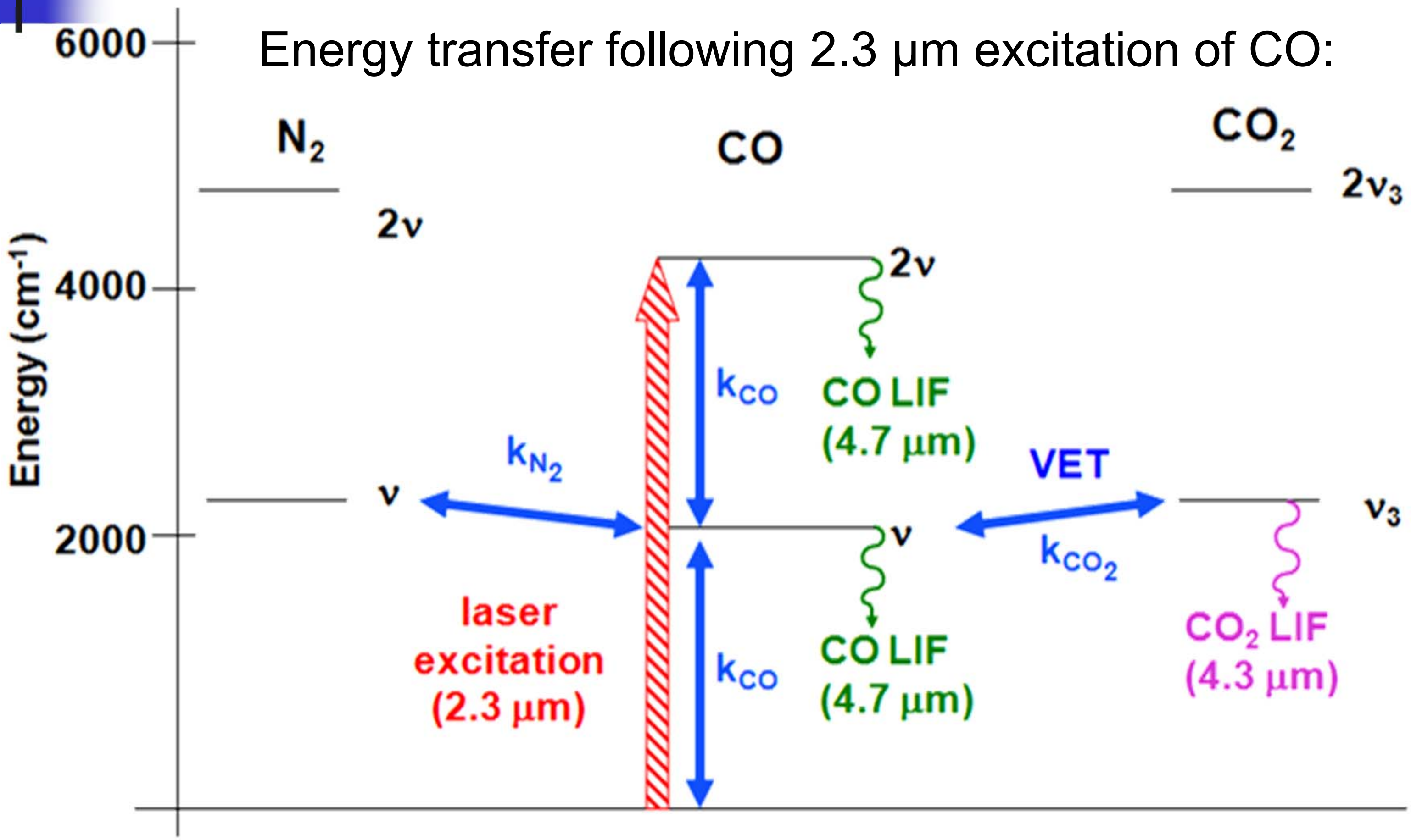
2.0 μm excitation
4.3 μm fluorescence

Infrared Planar Laser-Induced Fluorescence Imaging

- Potential to image species not easily accessible with Visible/UV PLIF
  - CO, CO_2, H_2O, hydrocarbons
- Advances in IR lasers sources and cameras have made IR PLIF possible
- First demonstrations of IR PLIF performed at Stanford (Kirby and Hanson)

3. PLIF with Molecular Vibrations in IR

Photophysics of Vibrational Fluorescence for CO and CO/CO_2 PLIF

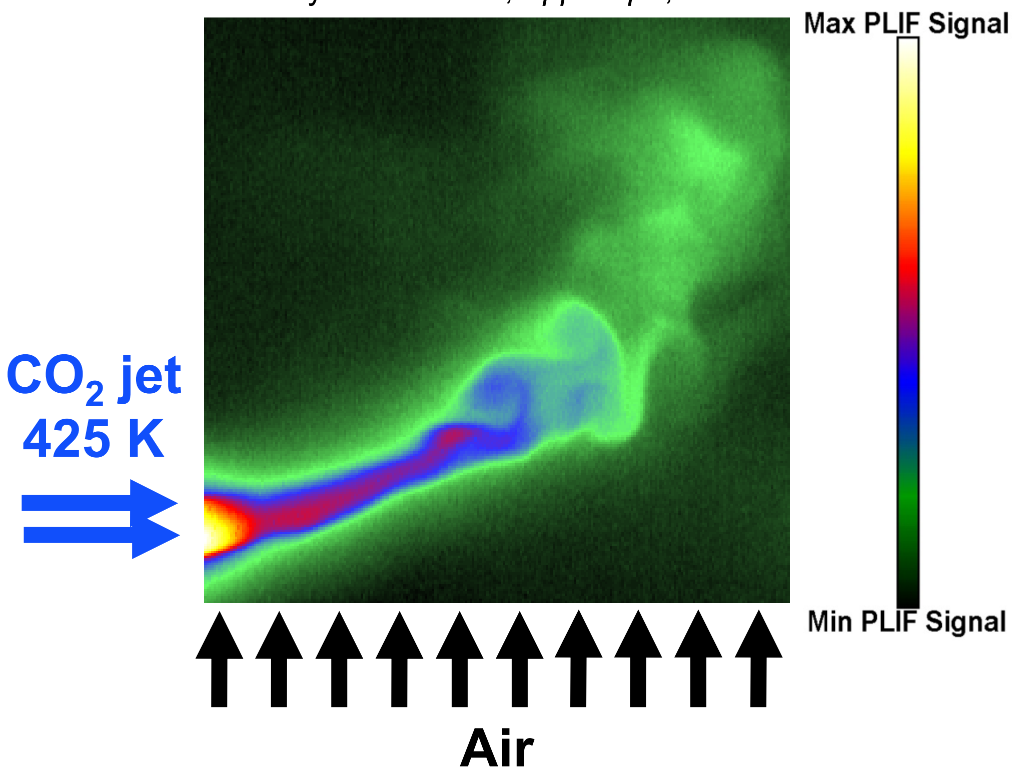


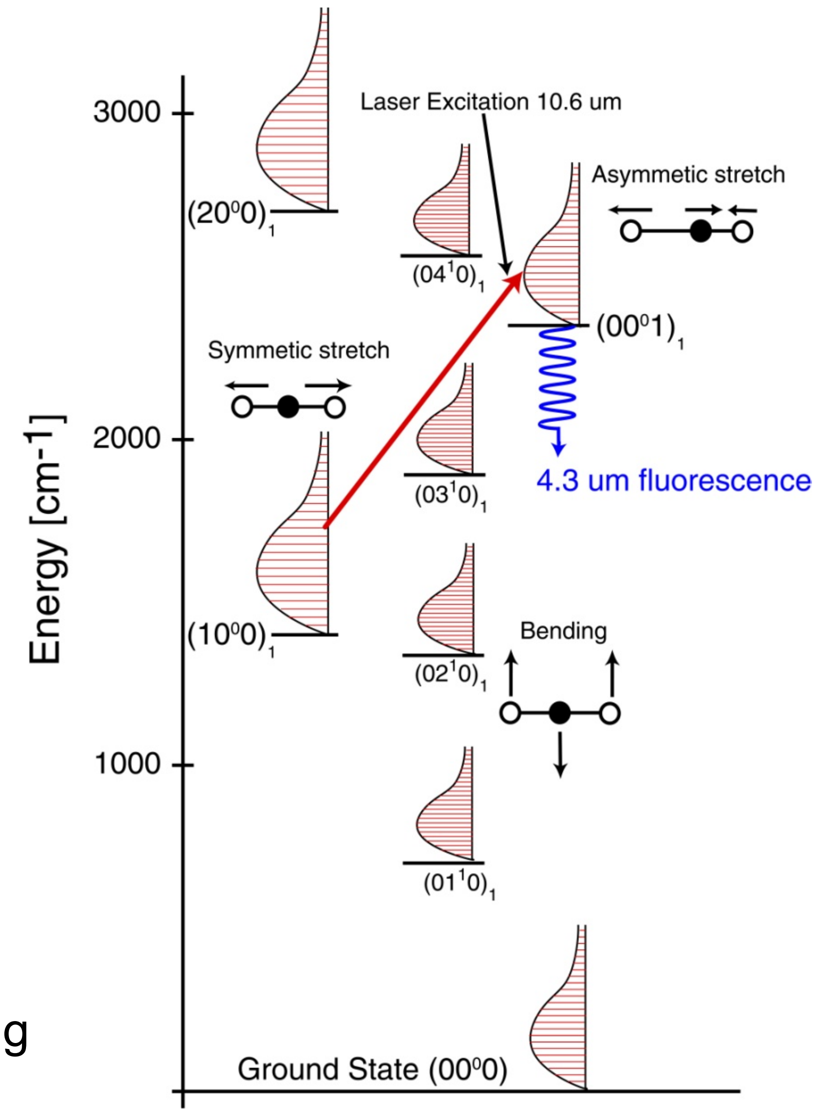
- Emission rates are low (100 s^{-1} vs 10^6 s^{-1})
- Energy transfer process can be slow (µs vs. ns)
- V-V transfer is typically faster than V-T transfer

3. PLIF with Molecular Vibrations in IR

Example of CO_2 Imaging: Using 10.6 µm Excitation

Kirby and Hanson, *Appl. Opt.*, 2000.





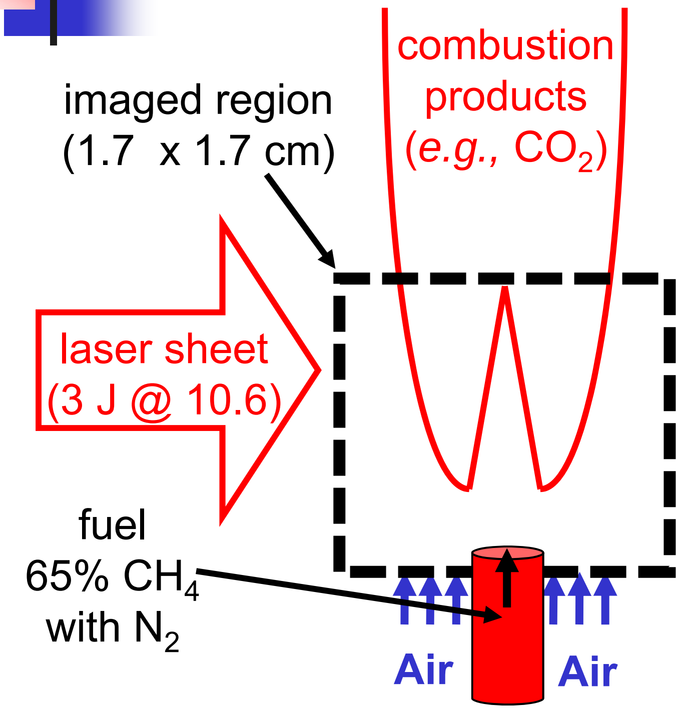
Transverse CO_2 jet (425K) in air cross flow

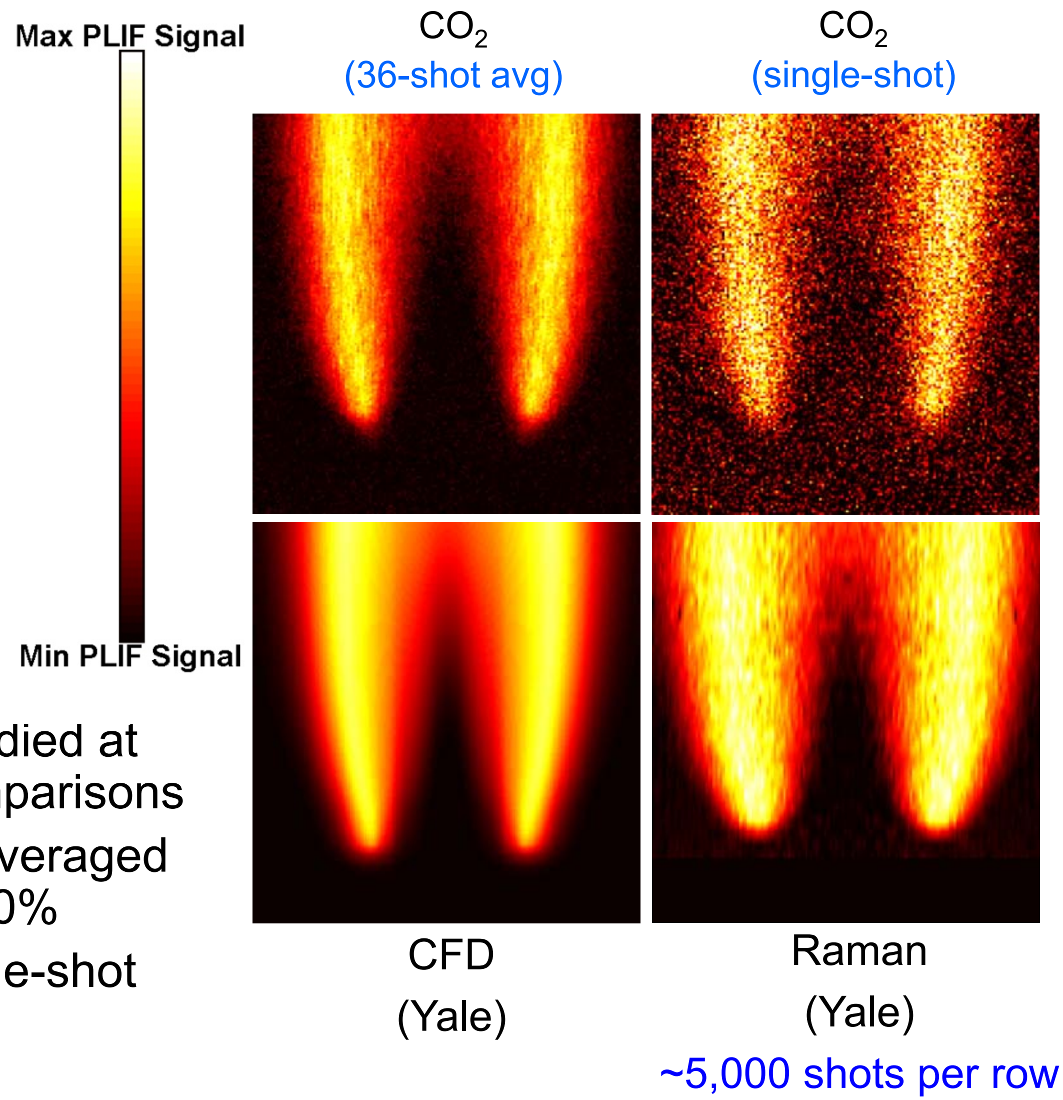
4.3 µm collection

- Demonstrates ability to image hot CO_2, mixing
- Potential for CO_2 imaging in flames

3. PLIF with Molecular Vibrations in IR

Comparison of CO_2 Images in a Lifted CH_4 Flame

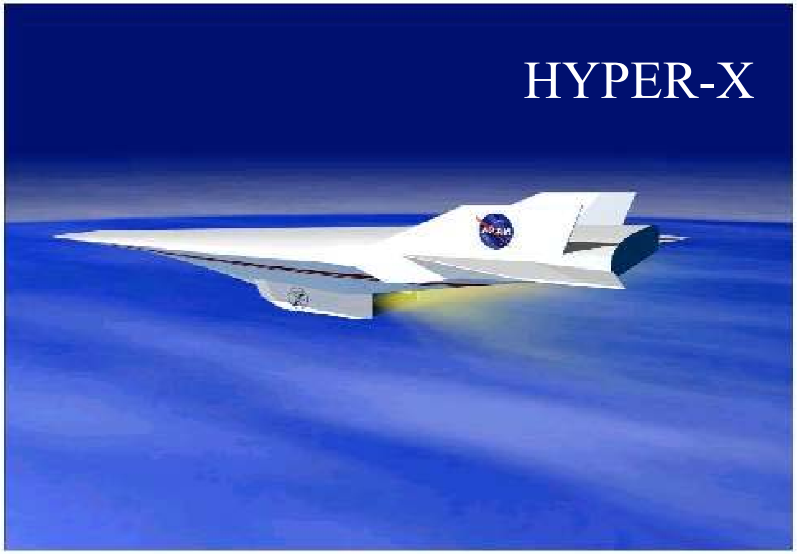




- Benchmark lifted CH_4 flame studied at Yale allows for quantitative comparisons
- IR PLIF agrees with CFD and averaged Raman measurements within 20%
- Demonstrates feasibility of single-shot imaging
- LIF signal >> Raman

4. Imaging Hypersonic Flows – Challenges

Diagnostic Challenges of SCRAMJETS: Opportunities for PLIF

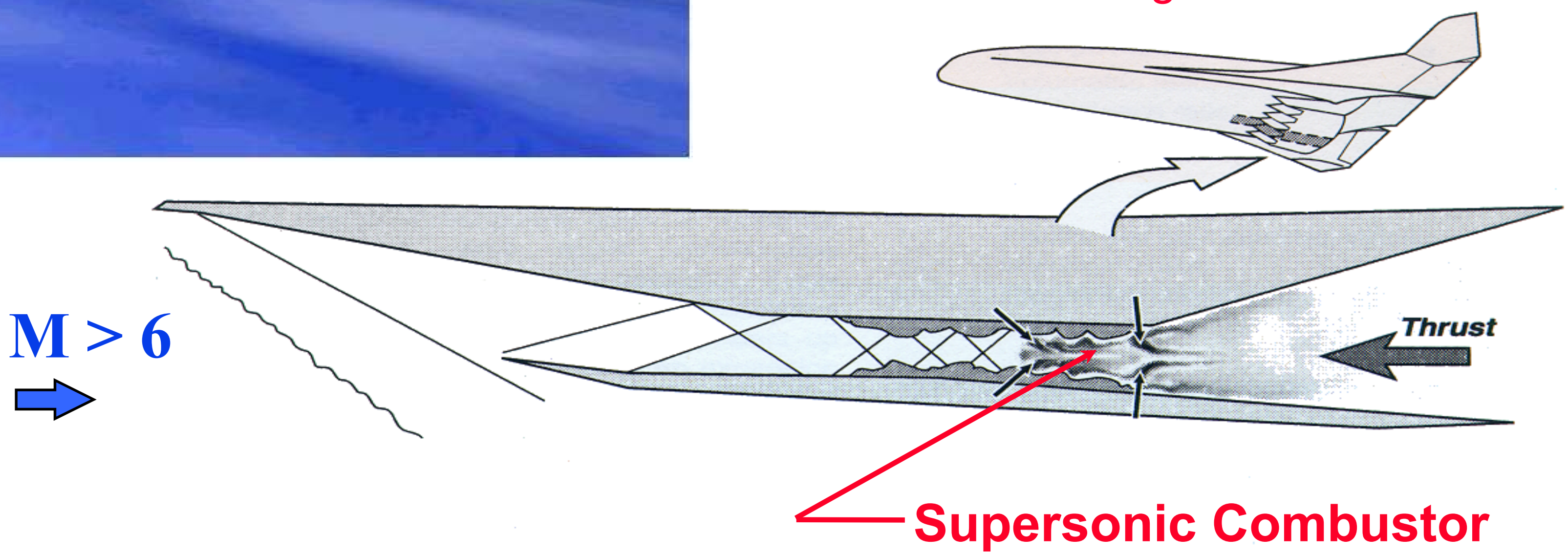


Research Issues:

- Autoignition and Flame-Holding
- Mixing

Diagnostic Issues:

- High-speed, harsh flow fields require non-intrusive diagnostics

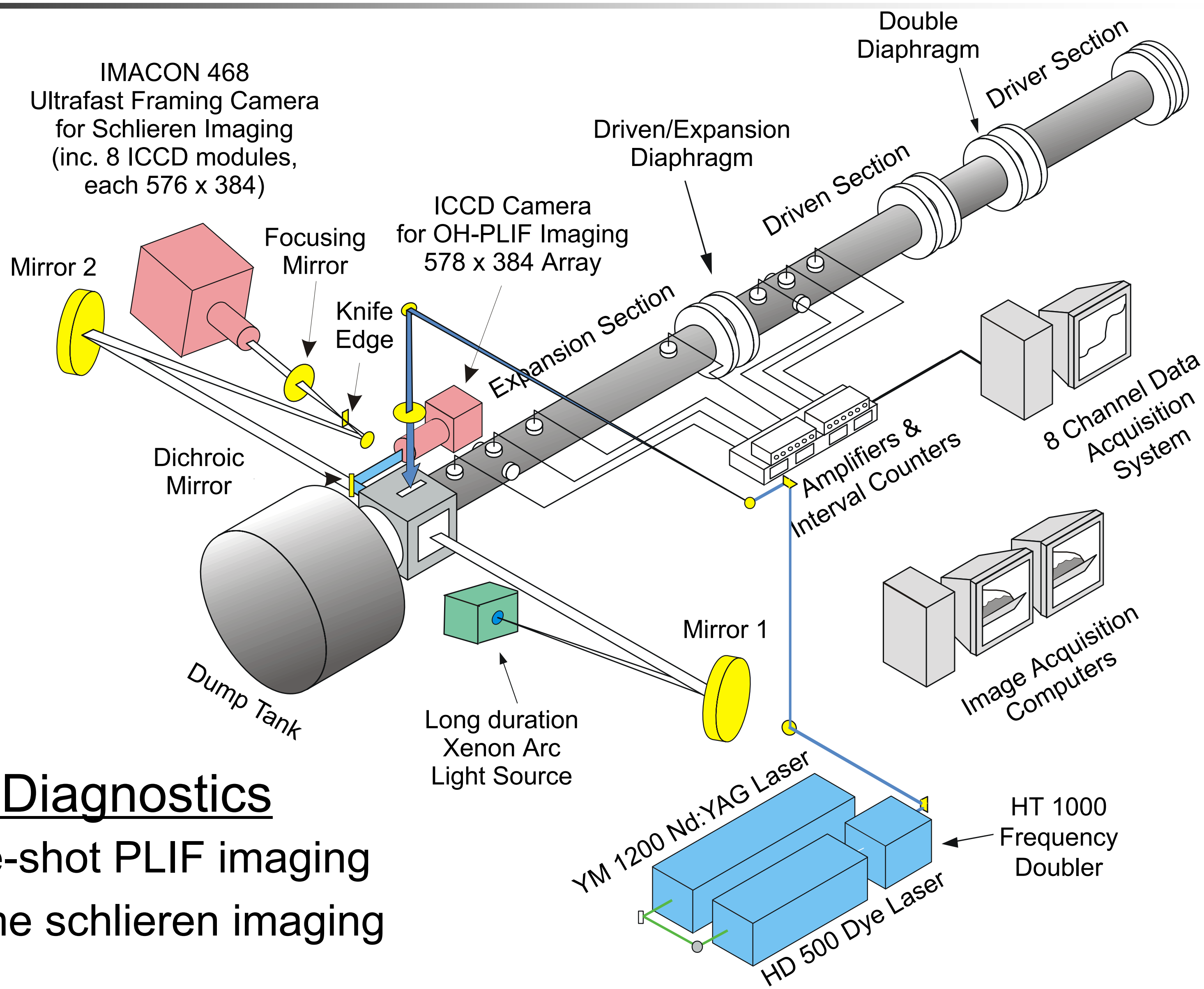


How do we do ground test beyond Mach 8?

Impulse Facilities: reflected shock tunnels, **expansion tubes**

4. Imaging Hypersonic Flows – Challenges

Stanford Expansion Tube Facility



Optical Diagnostics

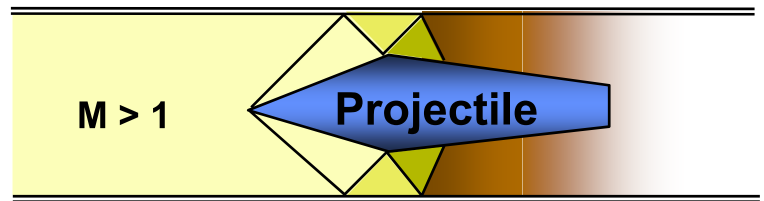
- Single-shot PLIF imaging
- 8-frame schlieren imaging

5. Imaging Hypersonic Flows – Reacting

A Tool to Study Ram Accelerator Phenomena

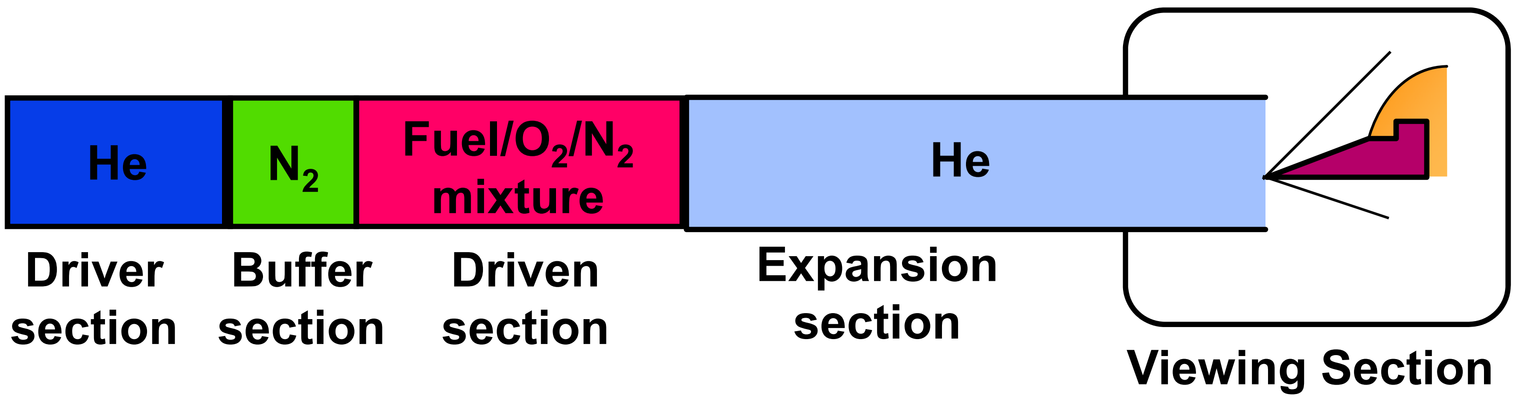
Measurement Strategy

- Fix projectile, flow gases, employ PLIF



Key issue

- Unsteady combustion/detonation



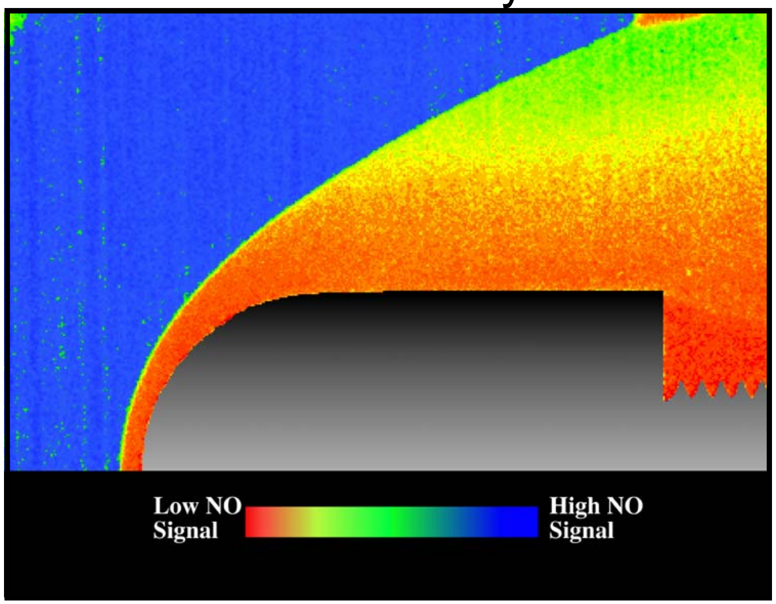
- Virtue of expansion tube: accelerates combustible gas to high velocity, with reduced exposure to high temperatures

5. Imaging Hypersonic Flows – Reacting

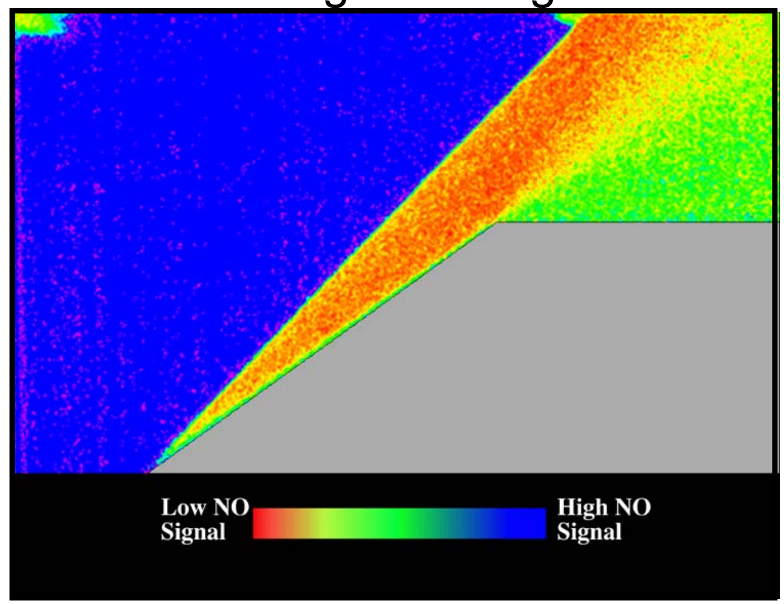
NO PLIF Imaging of Non-Reacting Flows

Mixture: 0.15% NO + 9.5% CH_4 + 90.35% N_2

19 mm Blunted Cylinder



40 degree Wedge



P_∞ = 0.063 atm, V_∞ = 2230 m/s, M_∞ = 7, T_∞ = 280 K

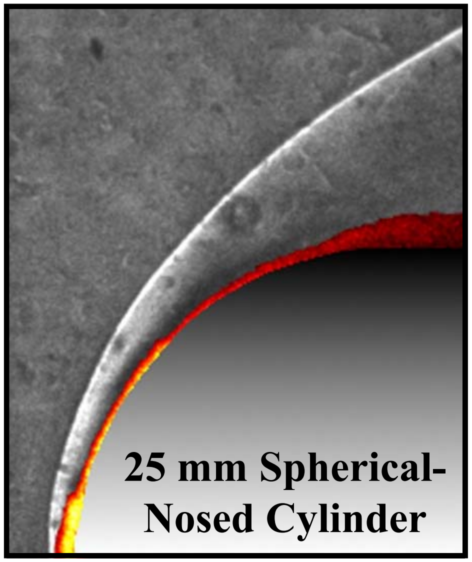
NO PLIF useful for shock wave visualization and quantitative flowfield determinations (T, P, χ_i)

5. Imaging Hypersonic Flows – OH PLIF in Reacting Flows

Simultaneous OH PLIF and Schlieren Imaging of Smooth Flame Front Regime: $V_\infty/V_{CJ} > 1$

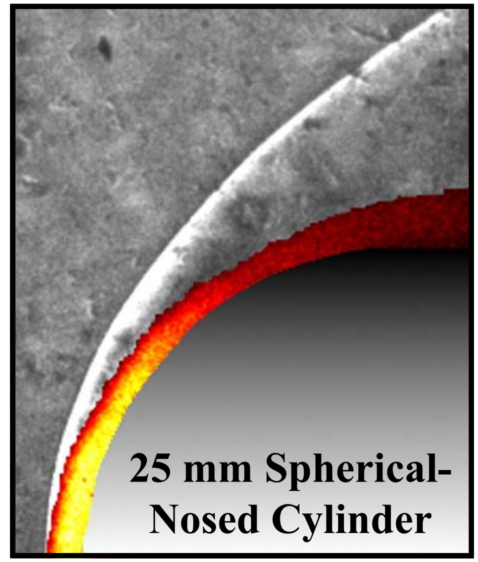
V_∞ = 2230 m/s , P_∞ = 0.07 bar, M_∞ = 6.3, T_∞ = 300 K

$V_\infty/V_{CJ} = 1.14$



16.7% CH_4 + 33.3% O_2 + 50.0% N_2
Mixture CJ velocity, V_{CJ} = 1950 m/s
t_{ign} ~ 10 μs

$V_\infty/V_{CJ} = 1.32$



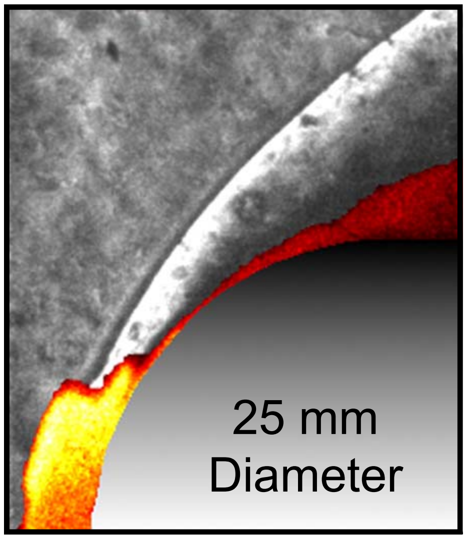
5% C_2H_4 + 15% O_2 + 80% N_2
Mixture CJ velocity, V_{CJ} = 1685 m/s
t_{ign} ~ 1 μs

- PLIF reveals steady combustion
- Peak OH in stagnation region

5. Imaging Hypersonic Flows – OH PLIF in Reacting Flows

Large Disturbance Regime: V_∞/V_{CJ} <1 Comparison with CFD Calculations

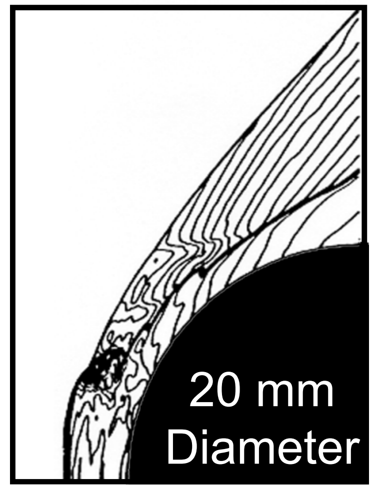
$V_\infty/V_{CJ} = 0.90$



10% C_2H_4 + 30% O_2 + 60% N_2

T_∞ = 420 K, P_∞ = .23 bar,
V_∞ = 1730 m/s

$V_\infty/V_{CJ} = 0.90$



Density contours from A. Matsuo & K. Fujii, AIAA 95-2565

Stoichiometric H_2/Air

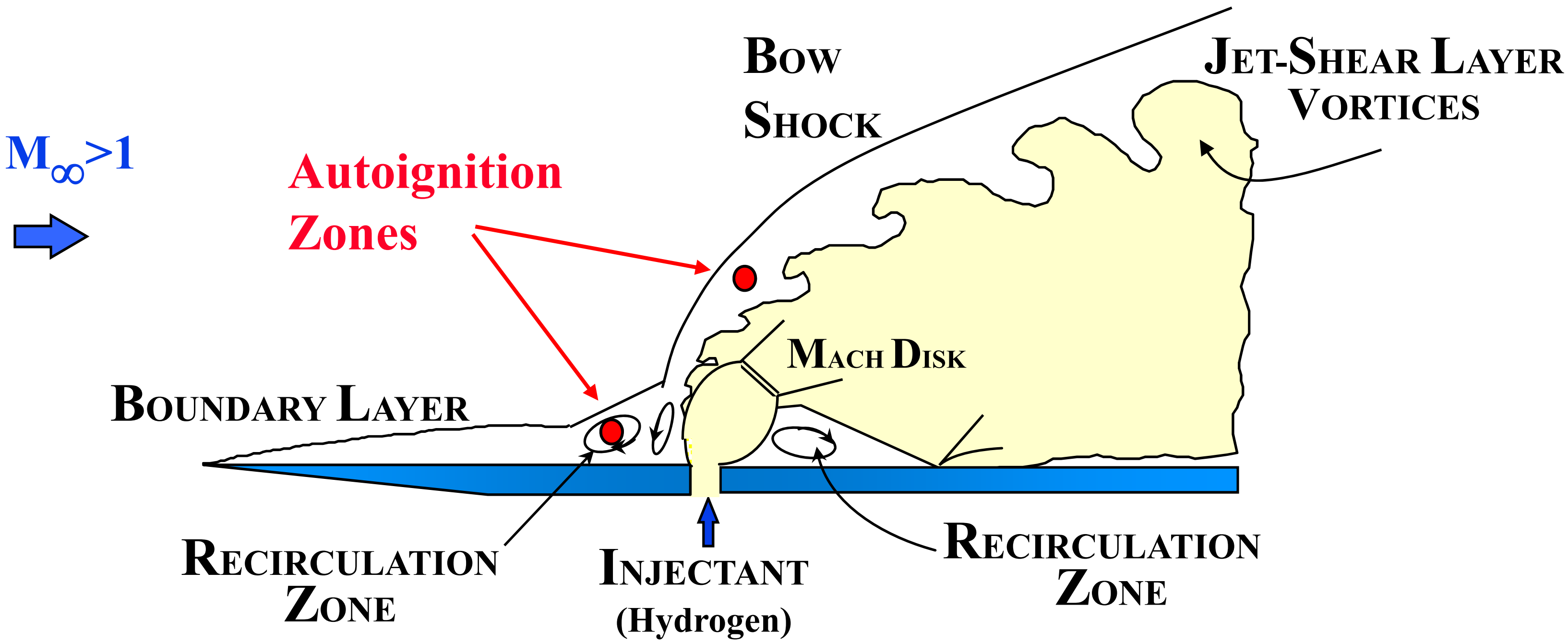
T_∞ = 300 K, P_∞ = 0.5 bar,
V_∞ = 1760 m/s

- Experimental results show good agreement with CFD calculations of large disturbance regime

5. Imaging Hypersonic Flows – Reacting

Critical Scramjet Issue: Mixing of Fuel

- Model problem: jet in supersonic crossflow



- 2-D imaging required to capture complex, unsteady flow structure
- Defining parameter: jet momentum ratio: $J = (ru^2)_{jet}/(ru^2)_\infty$

5. Imaging Hypersonic Flows – Reacting

H_2 Jet in Supersonic Crossflow Imaging with Schlieren

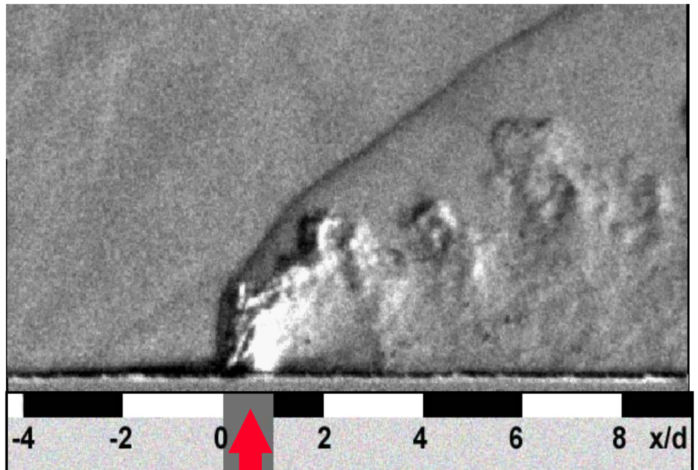
Nitrogen →

M_∞= 3.4

V_∞= 2360 m/s

P_∞= 0.32 atm

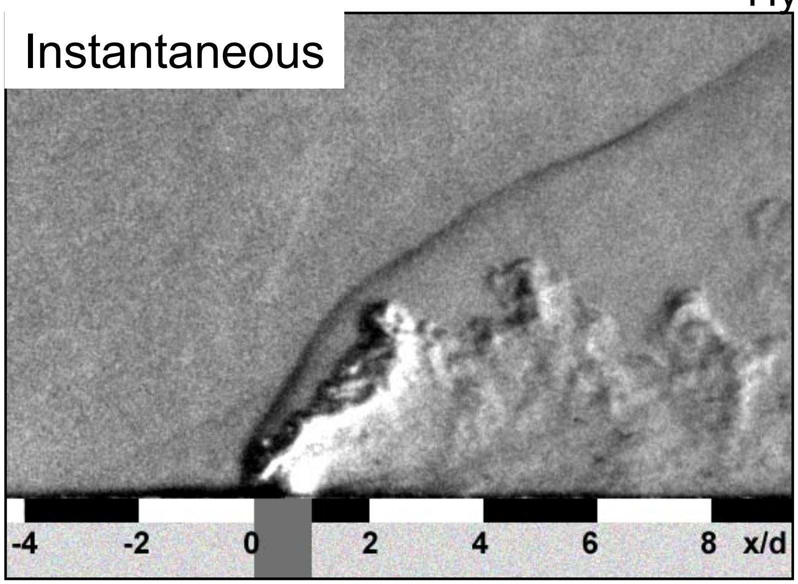
T_∞= 1290 K



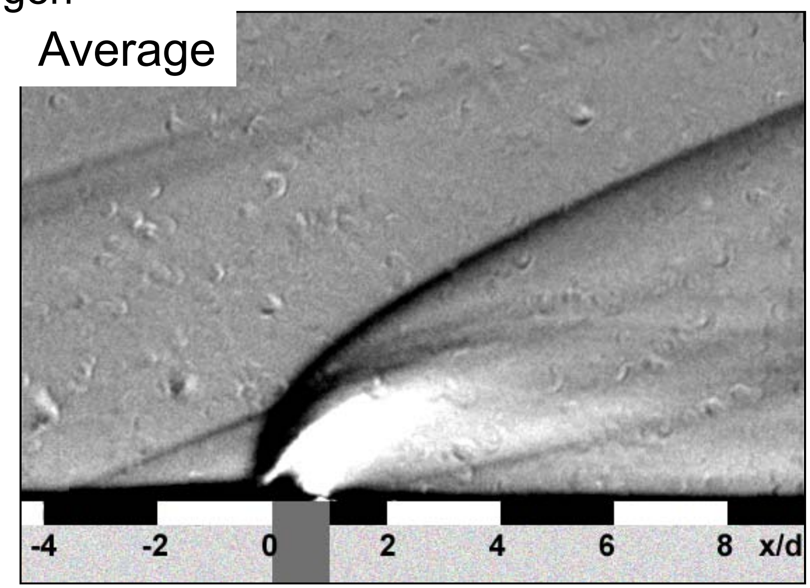
Hydrogen

← 0.1 μs exposure
8-frame movie with
1ms framing time
shows flow structure

↓ 10 μs exposure



Instantaneous



Average

- Use of short gating times reveals unsteady flow structure

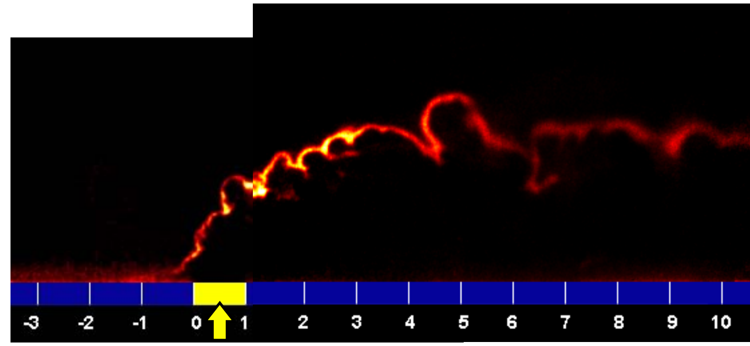
5. Imaging Hypersonic Flows – OH PLIF in Reacting Flows

PLIF Imaging of OH in Combusting Jet

Defining Eqn:

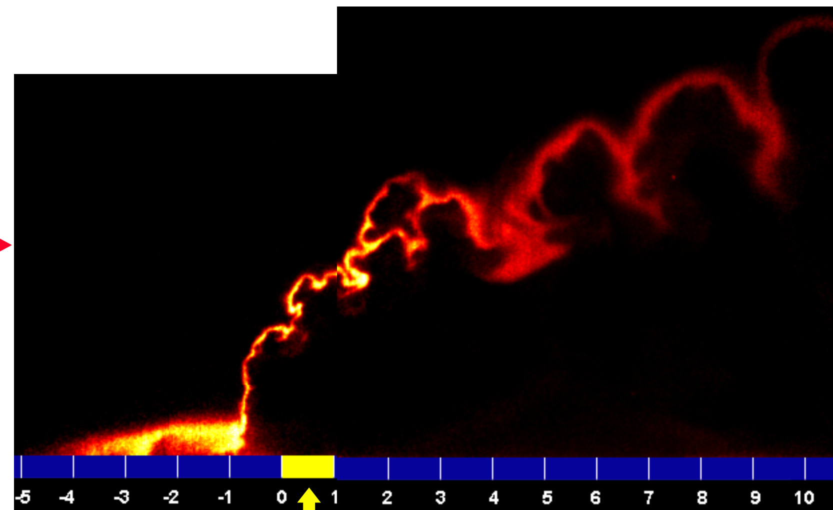
$$S_f \propto X_{OH} \cdot f(T)$$

Mach 10
Air
M_∞= 3.4
V_∞= 2360 m/s
P_∞= 0.32 atm
T_∞= 1290 K



H_2 , J=1.4

Mach 13
Oxygen
M_∞= 4.7
V_∞= 3200 m/s
P_∞= 0.04 atm
T_∞= 1250 K



H_2 , J=5

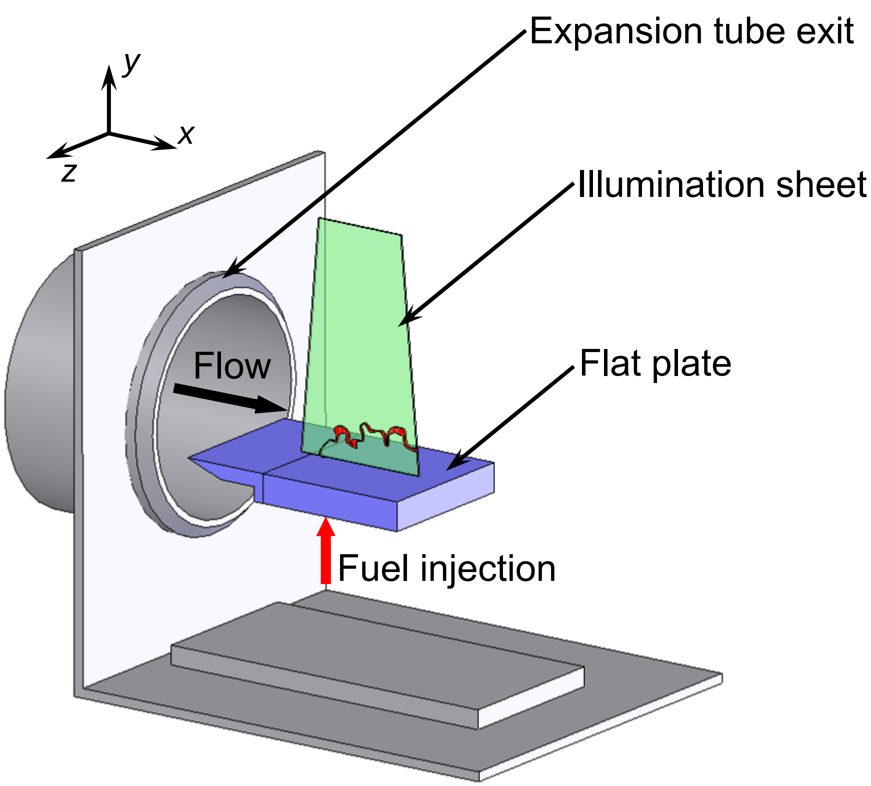
Key Observations

- Penetration increases with jet momentum ratio (J)
- Increased recirculation zone enhances flame holding
- Reaction zone width increases with x/d

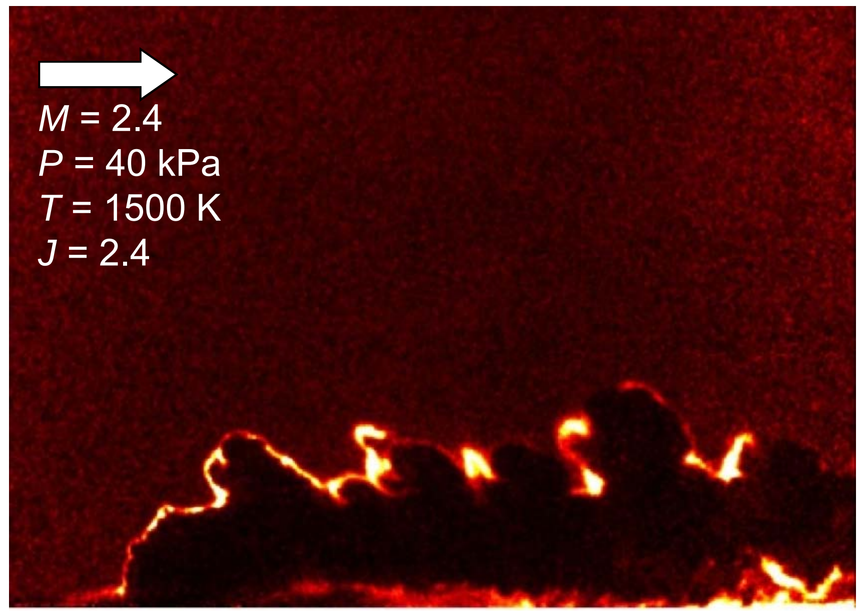
5. Imaging Hypersonic Flows – OH PLIF in Reacting Flows

- Flame Structure of Hydrogen Jet in Supersonic Crossflow (Combine Side-view, Plan-view and Transverse-plane Images)

Schematic diagram of imaging experiments



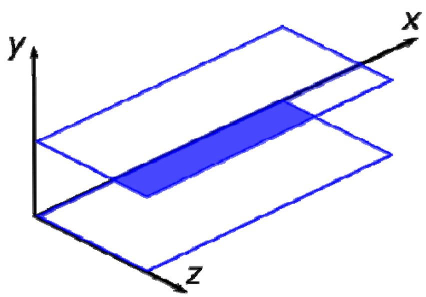
Planar laser-induced fluorescence of hydroxyl radical marking the instantaneous reaction zone of hydrogen jet in supersonic crossflow

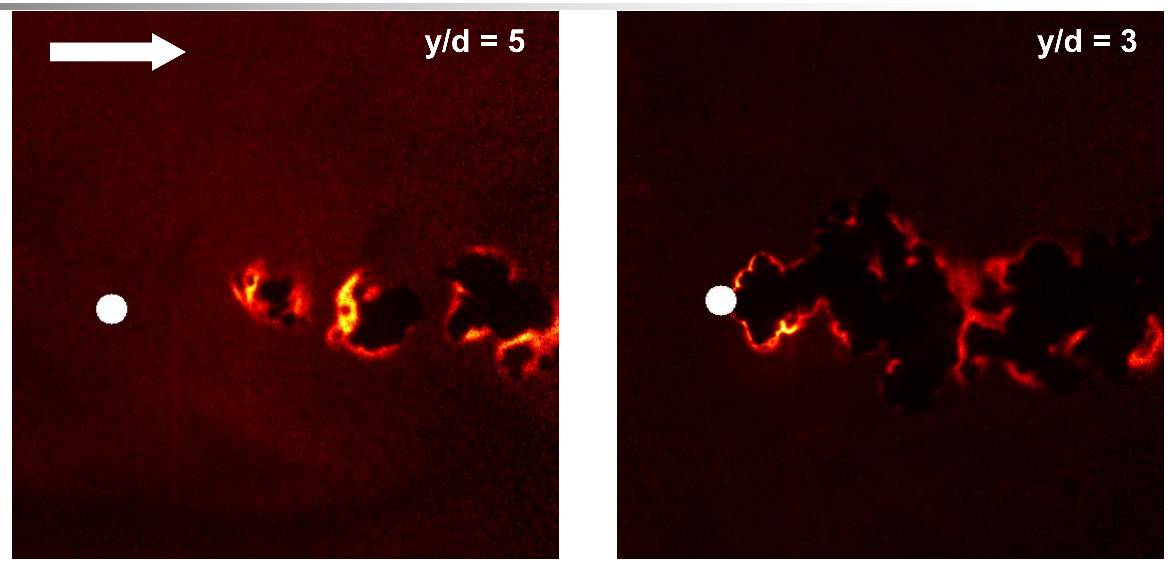


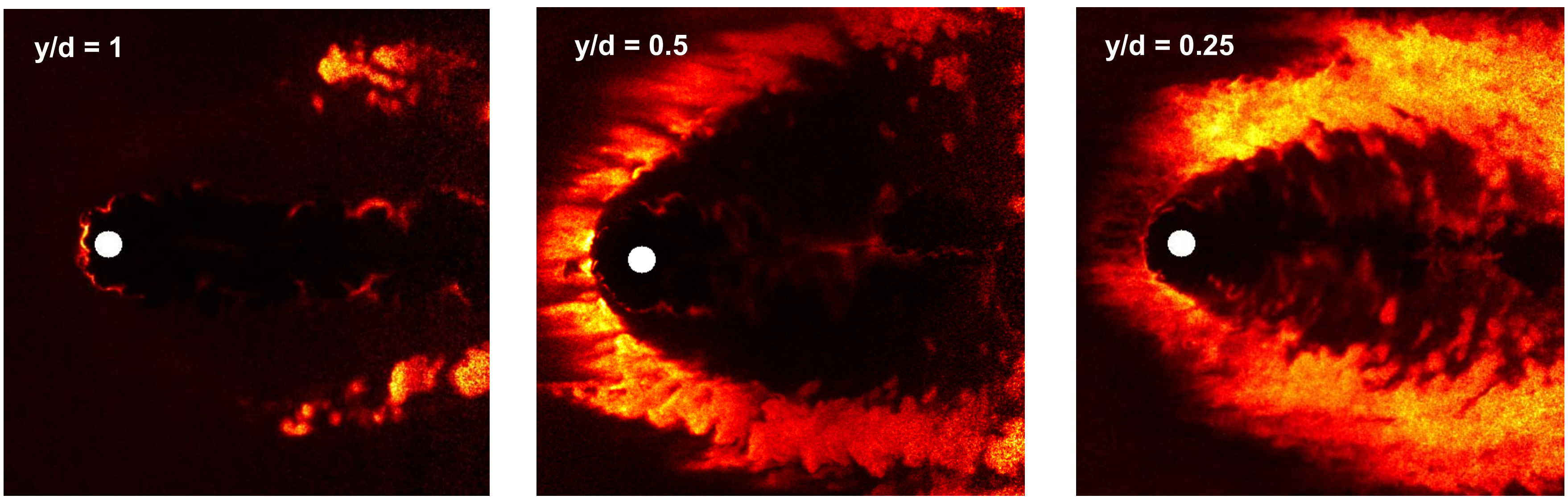
5. Imaging Hypersonic Flows – OH PLIF in Reacting Flows

Flame Structure of Hydrogen Jet in Supersonic Crossflow

Plan-views



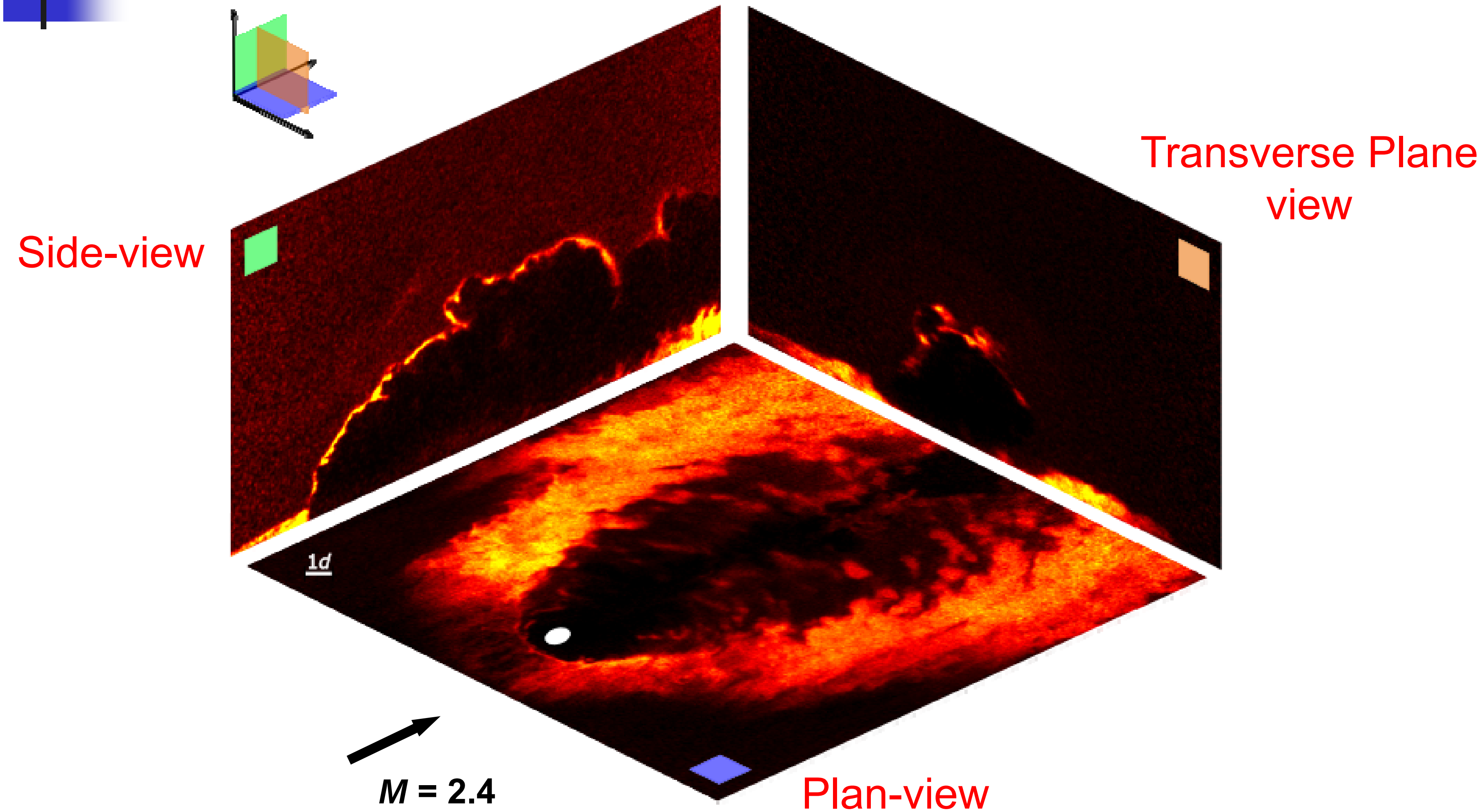




Images adapted from Heltsley (2009)

5. Imaging Hypersonic Flows – OH PLIF in Reacting Flows

Flame Structure of Hydrogen Jet in Supersonic Crossflow

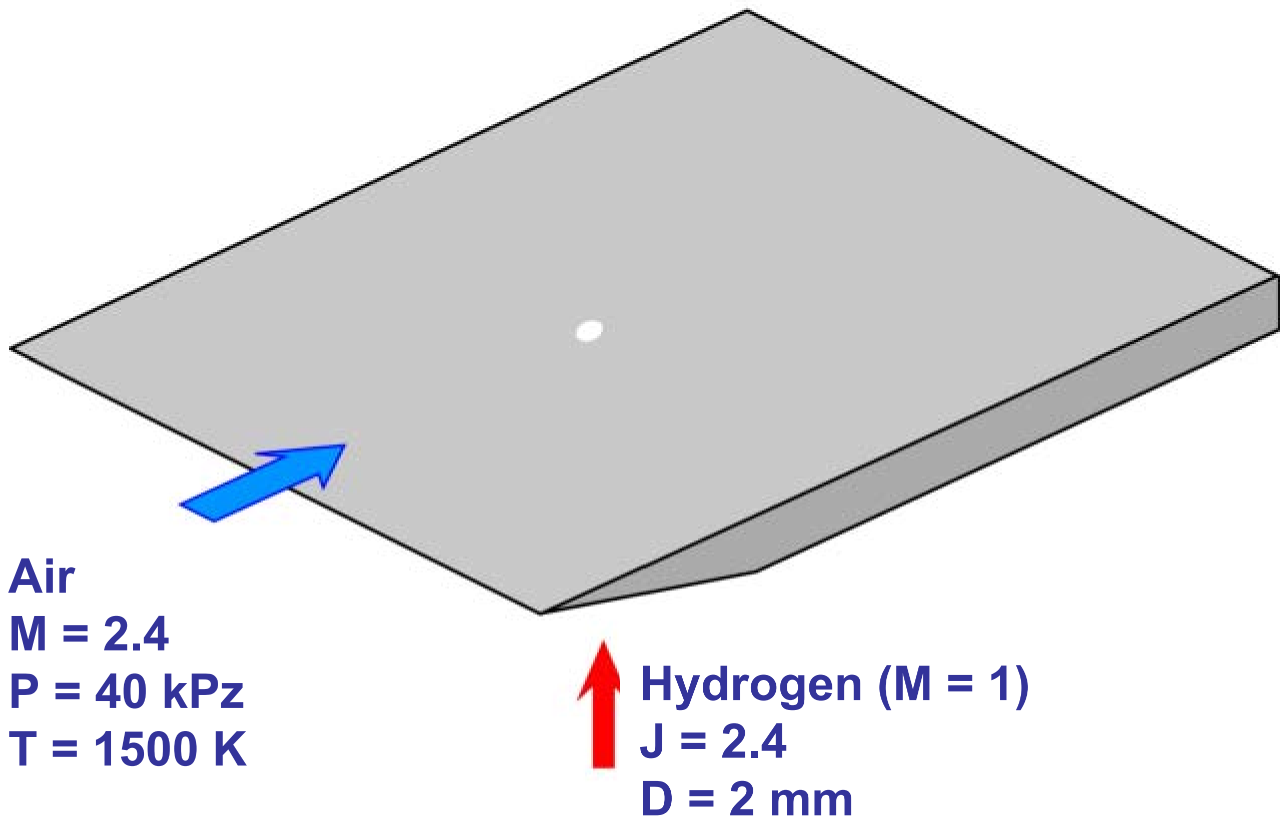


M **= 2.4**
P **= 40 kPa**
T **= 1500 K**
J **= 2.4**

Adapted from Heltsley (2009)

5. Imaging Hypersonic Flows – OH PLIF in Reacting Flows

OH PLIF images trace the 3-D structure of the flame

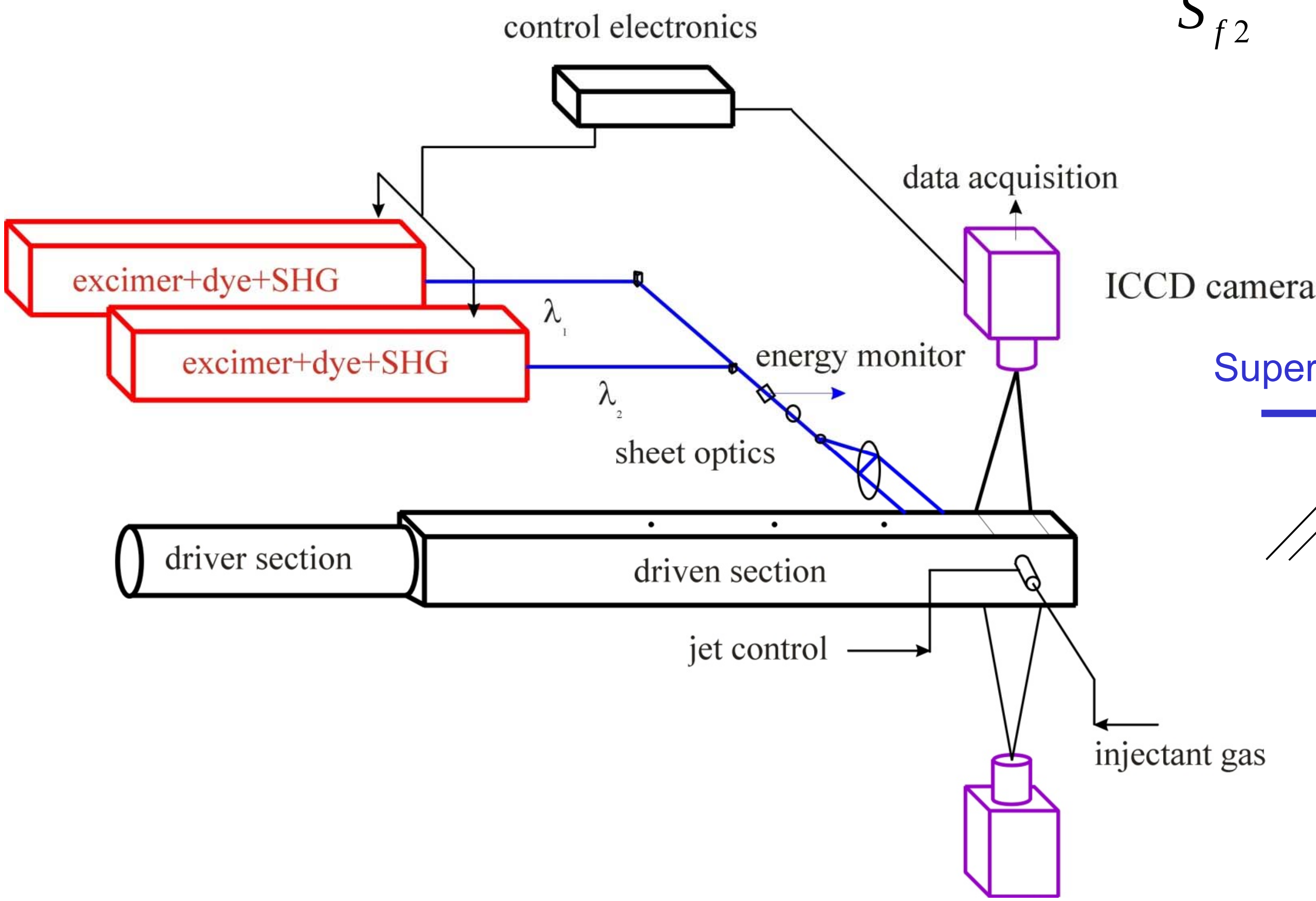


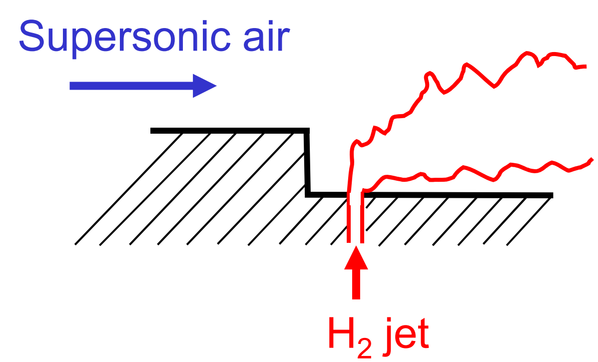
6. Imaging Hypersonic Flows – T w NO (2 camera)

Extension of PLIF Imaging to Scramjet Flow Using 2 Lasers for T

- Instantaneous temperature imaging
- Instantaneous multi-species imaging

$$R_{12} \equiv \frac{S_{f1}}{S_{f2}} = C_{12} \exp\left[\frac{-\Delta\varepsilon_{12}}{k \cdot T}\right]$$



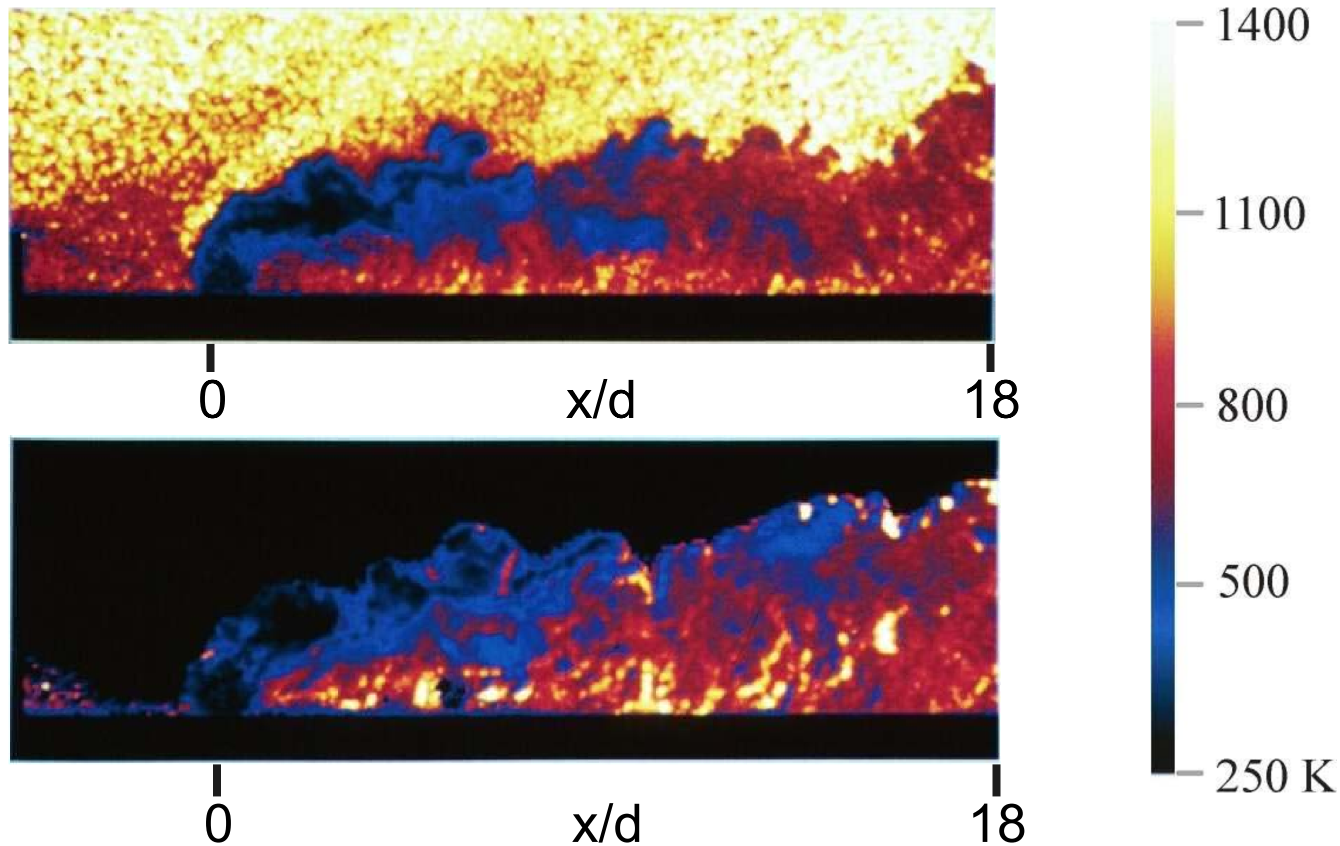


6. Imaging Hypersonic Flows – T w NO (2 camera)

Instantaneous, Two-Line NO Temperature Images

With NO in freestream

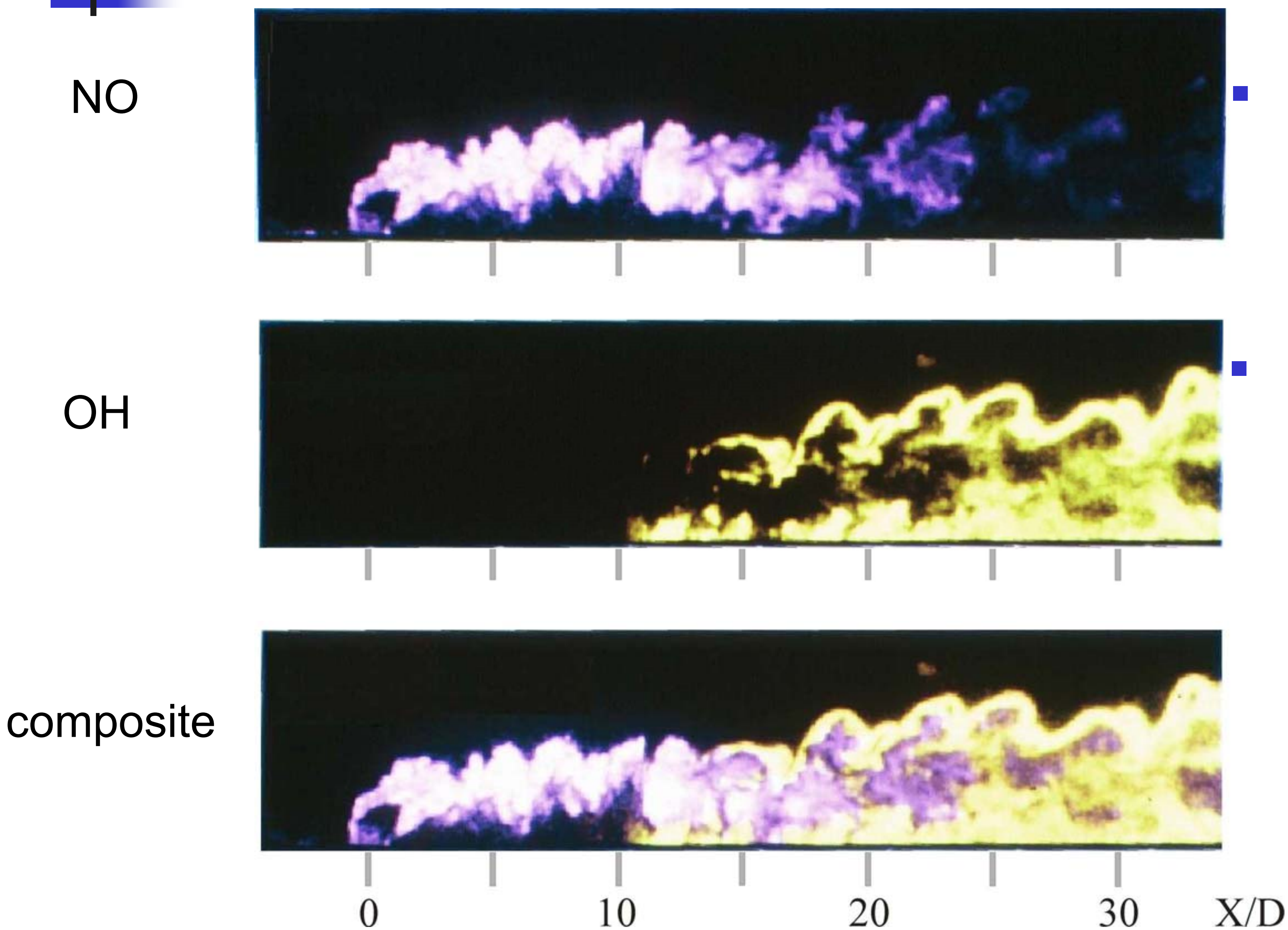
Without NO in freestream



- Instantaneous T determined to ±50 K in 300 K-1400 K range
- Images reveal:
  - Jet mixing requires x/d ~ 12
  - Heated boundary layer provides ignition

6. Imaging Hypersonic Flows – Dual Species

Simultaneous NO and OH Imaging

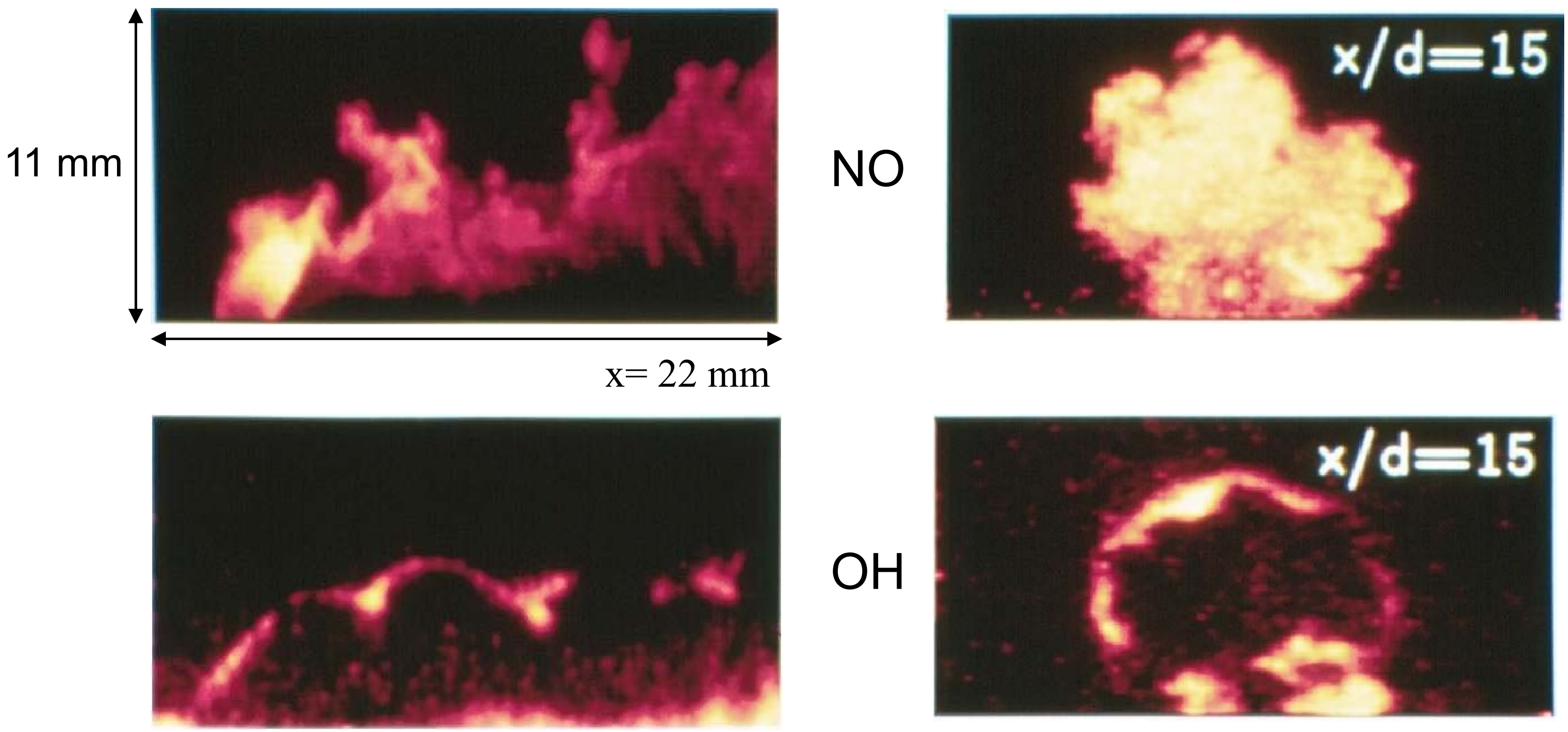


- Reveals mixing
- Reveals combustion zones

6. Imaging Hypersonic Flows – Dual Species

Comparison of Axial and Transverse Plane Images

- Freestream: M=1.4, P=0.4 atm, T=2200 K
- Jet: P_o=3 atm, T_o=300 K, d=2 mm



- NO image reveals efficient mixing by x/d = 15
- OH image reveals that combustion occurs at jet periphery and in boundary layer

Next Lecture

Applications of LIF and PLIF using flow tracers

1. PLIF of ketone hydrocarbons
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
7. Two camera toluene PLIF for temperature