The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

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Winter College on Optics in Environmental Science

2 - 18 February 2009

Combustion basics, Laser diagnostics of combustion
Part I

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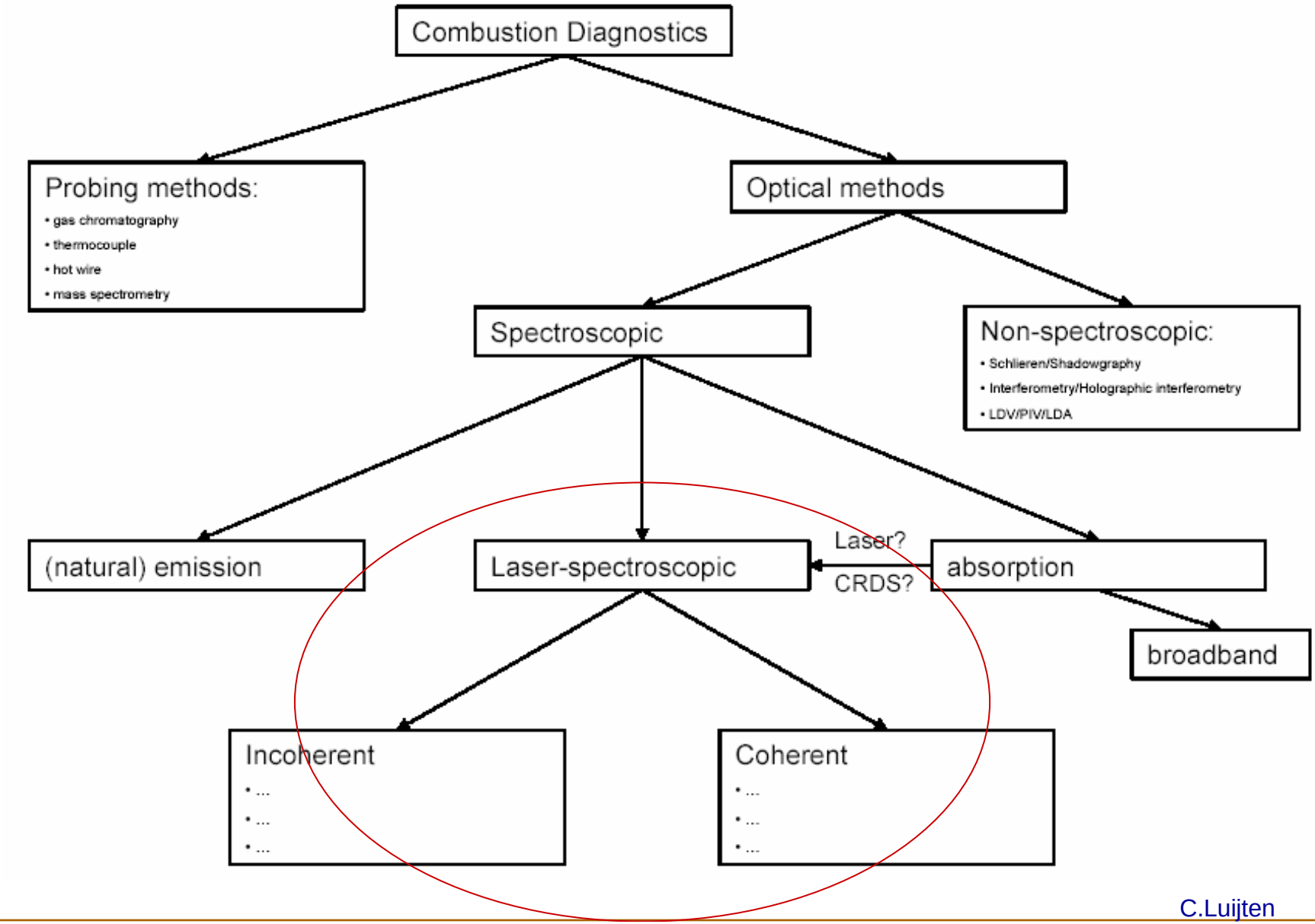
Combustion diagnostics



C.Luijten

Combustion diagnostics

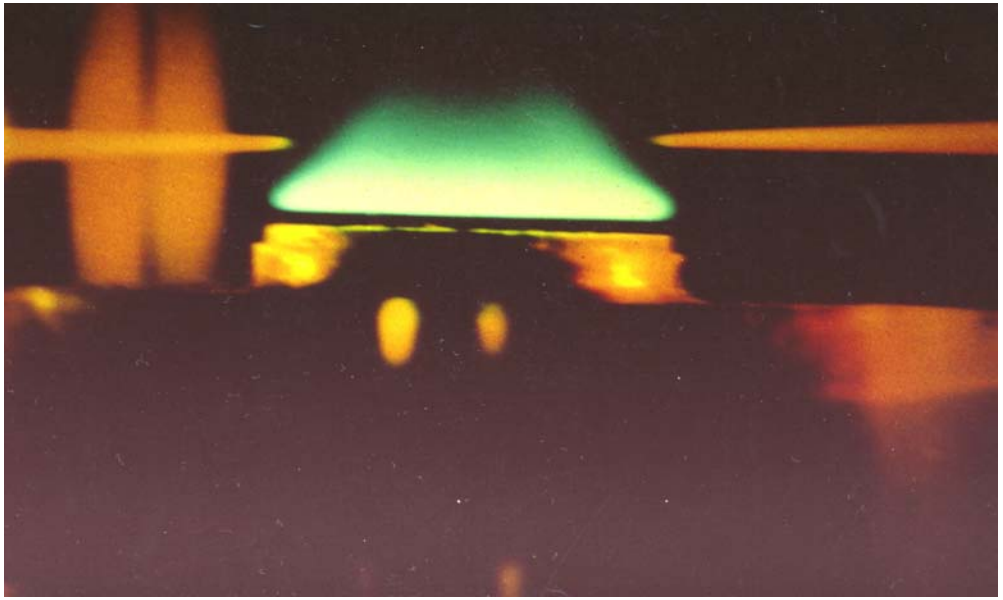
Diagnostics used for measurements of:

- Species concentrations
- Pressure
- Temperatures
- Velocities
- Particle characteristics (number density/size)
- Surface characteristics

Objectives with Diagnostic Techniques for Combustion Characterization

- Development of new diagnostic techniques as well as fundamental studies of these new as well as established techniques (e.g investigations of spectral behaviour at 30 bar, 3000 K)
- Applications of the more developed techniques for measurements of relevant parameters, e.g. species concentrations, temperatures, velocities and particle characteristics for phenomenological studies (e.g investigations of turbulent combustion)
- Applications of mature techniques for characterisation, optimisation and control of industrial processes (e.g investigations of IC engine performances)

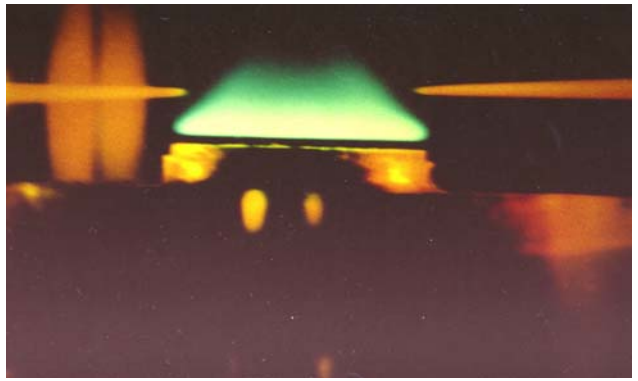
Why lasers in combustion diagnostics ?



- Non-intrusive
- High spatial resolution (<0.001 mm^3)
- High temporal resolution (<10 ns)
- High spectral resolution (~MHz)
- Multiplex (multi-species, multi-point)
- Can measure non-thermal equilibrium

Potential drawbacks with lasers in combustion diagnostics ?

- Complicated
- Expensive
- Eye safety
- Optical access required
- Intrusive?
  - Laser-induced breakdown
  - Creation of molecular fragments; atoms
  - Optical pumping

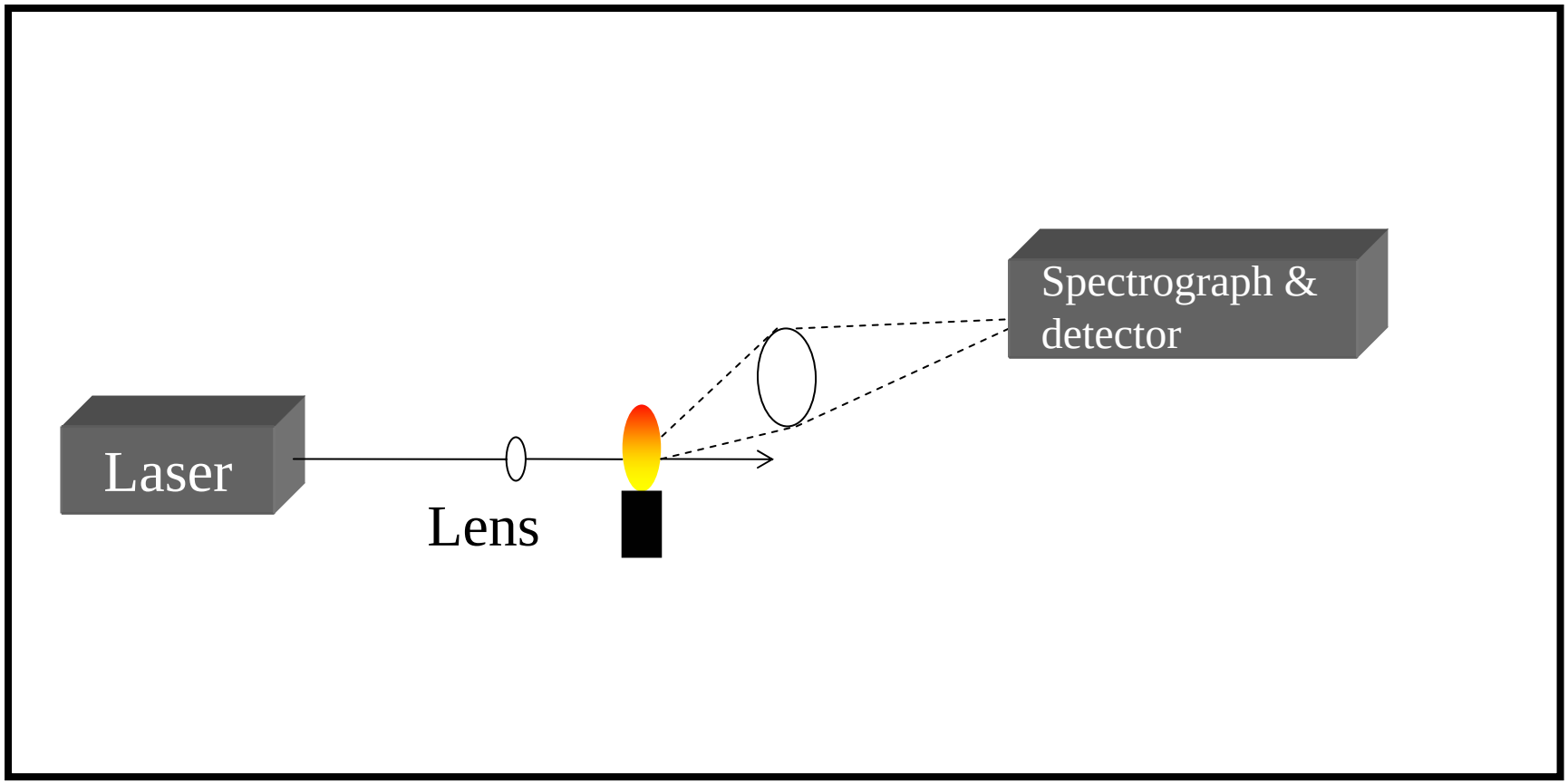


Laserdiagnostics in combustion

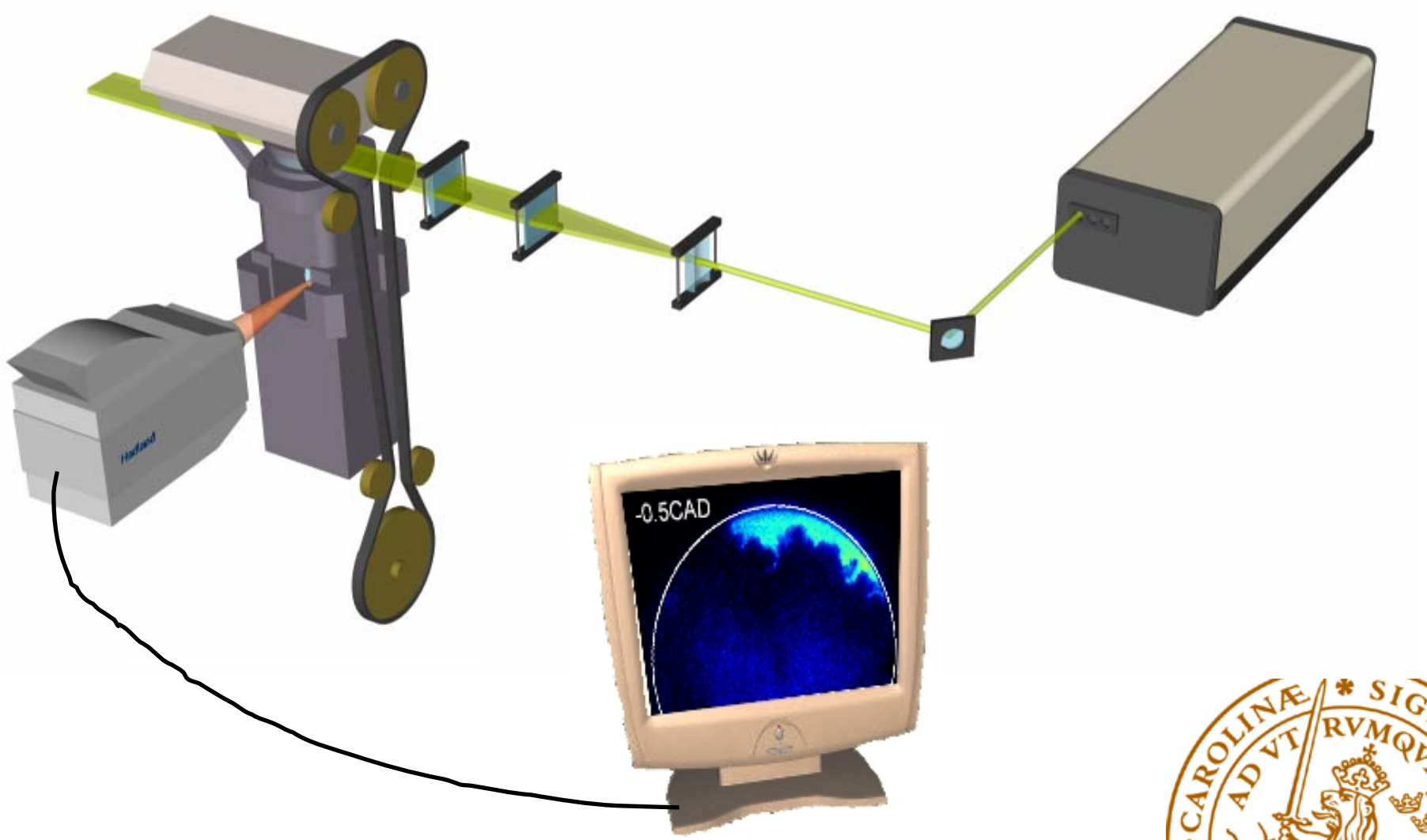
What can be measured ?

- Temperatures (rotational/vibrational/ translational/electron)
- Species concentrations (molecules, radicals, atoms)
- Velocities
- Particle number densities/diameters
- Surface characteristics
- Two-phase characterization

Set-up incoherent scattering



Incoherent measurements

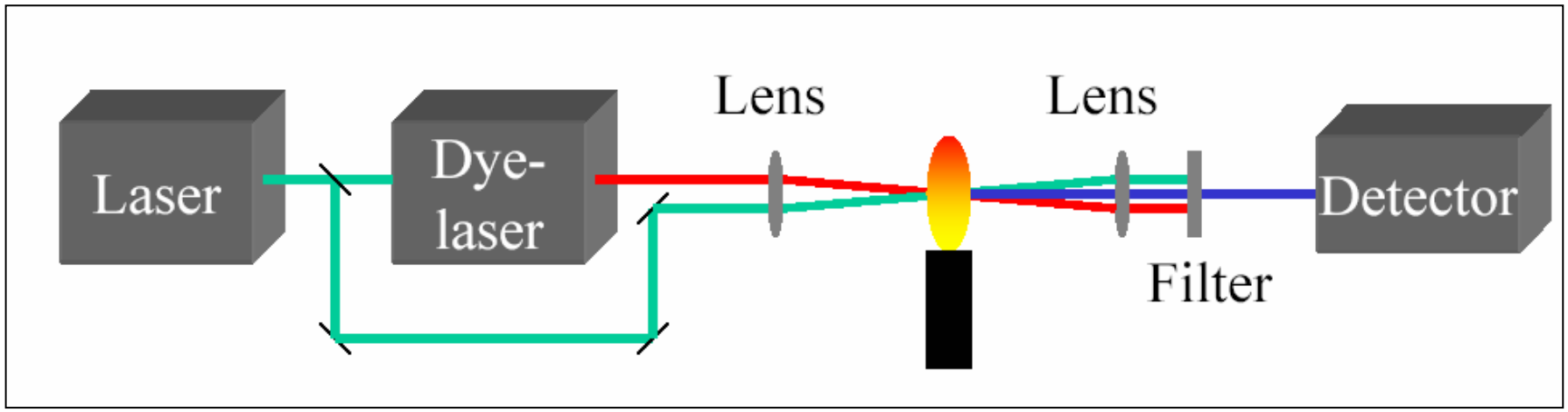


Laser techniques

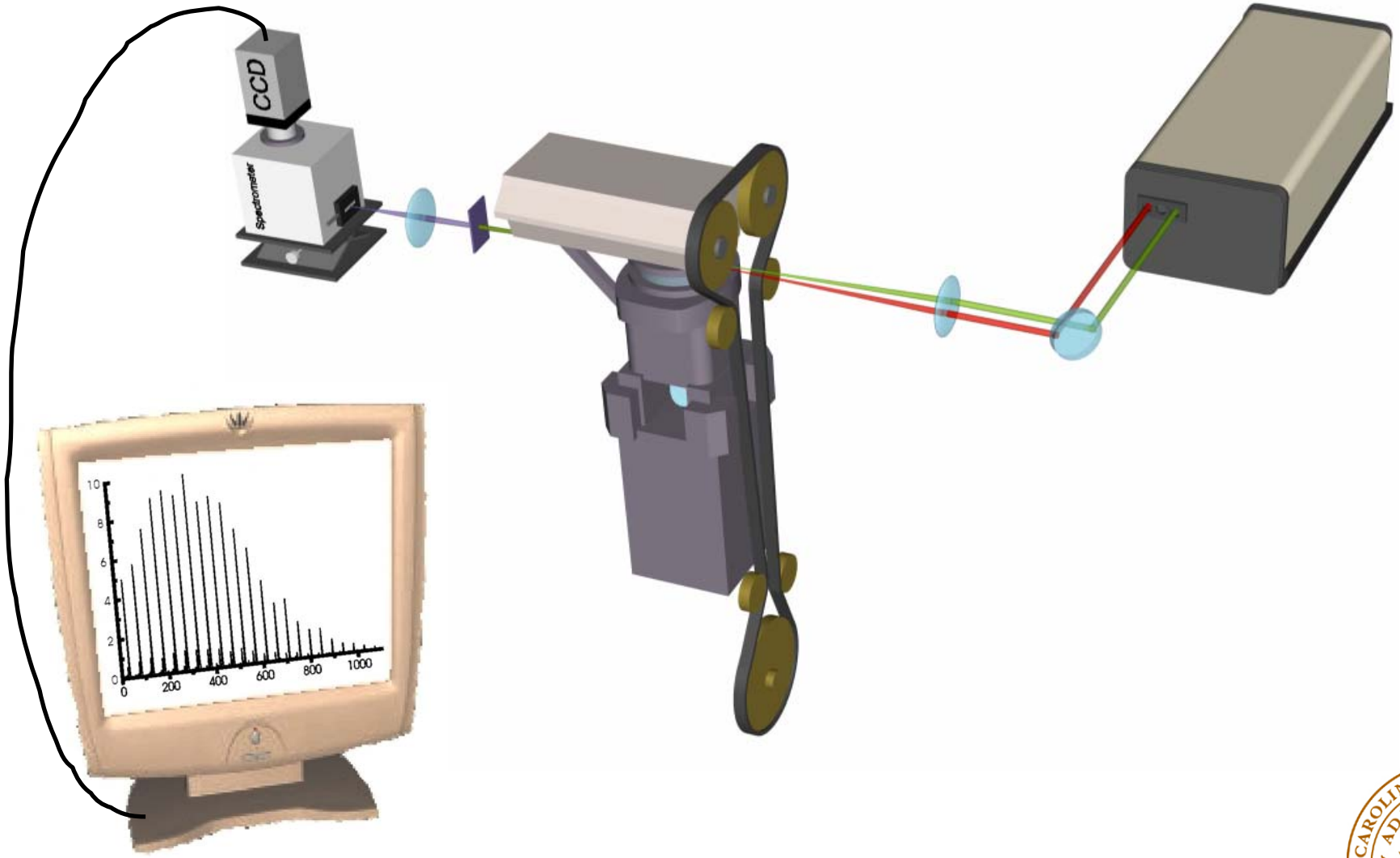
Incoherent techniques:

- Mie/Rayleigh scattering
- Laser-induced fluorescence (LIF)
- Laser-induced incandescence (LII)
- Raman scattering

Set-up coherent scattering



Coherent measurement



Laser techniques

Coherent techniques:

- CARS
- Polarisation spectroscopy
- DFWM
- Stimulated emission, SE

Short history: Combustion Laser Diagnostics

- First papers on combustion applications in the early seventies; Raman/Rayleigh applications
- First Engine /GT applications during the eighties; LIF developments
- Multidimensional visualization, non-linear techniques during the ninties
- Multiple technique applications, quantitative real-world applications during 2000-

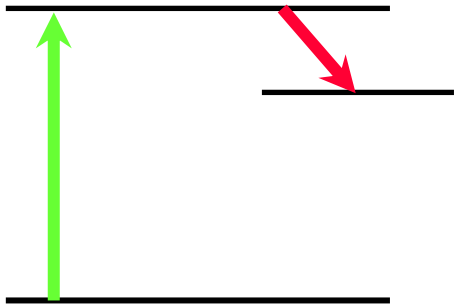
Practical applications of laser diagnostics: Special challenges

- High pressure
- Limited optical access
- Sooty environment
  - Laser-induced break-down
  - Laser-induced incandescence
  - Mie scattering
- Practical fuels
  - Extinction, trapping
  - Laser-induced background fluorescence (e.g. from large HC)
  - Photolytic effects, e.g. laser-induced C_2 emission
- Window scattering/damages/fouling

Laser-induced fluorescence

LIF:

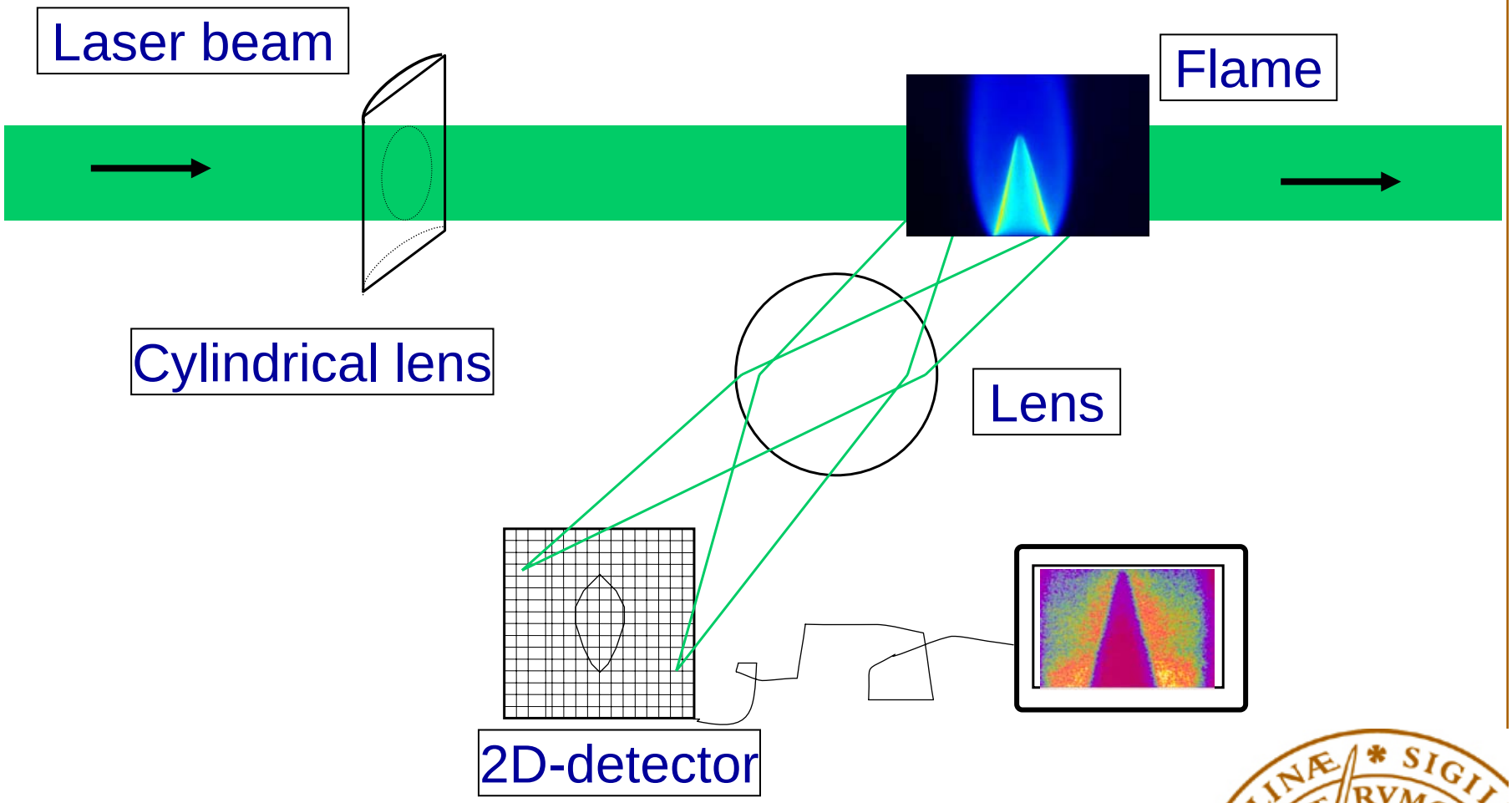
Measures e.g, NO, OH,
CH, CN, C_2, O_2, CH_2O, fuel-tracer

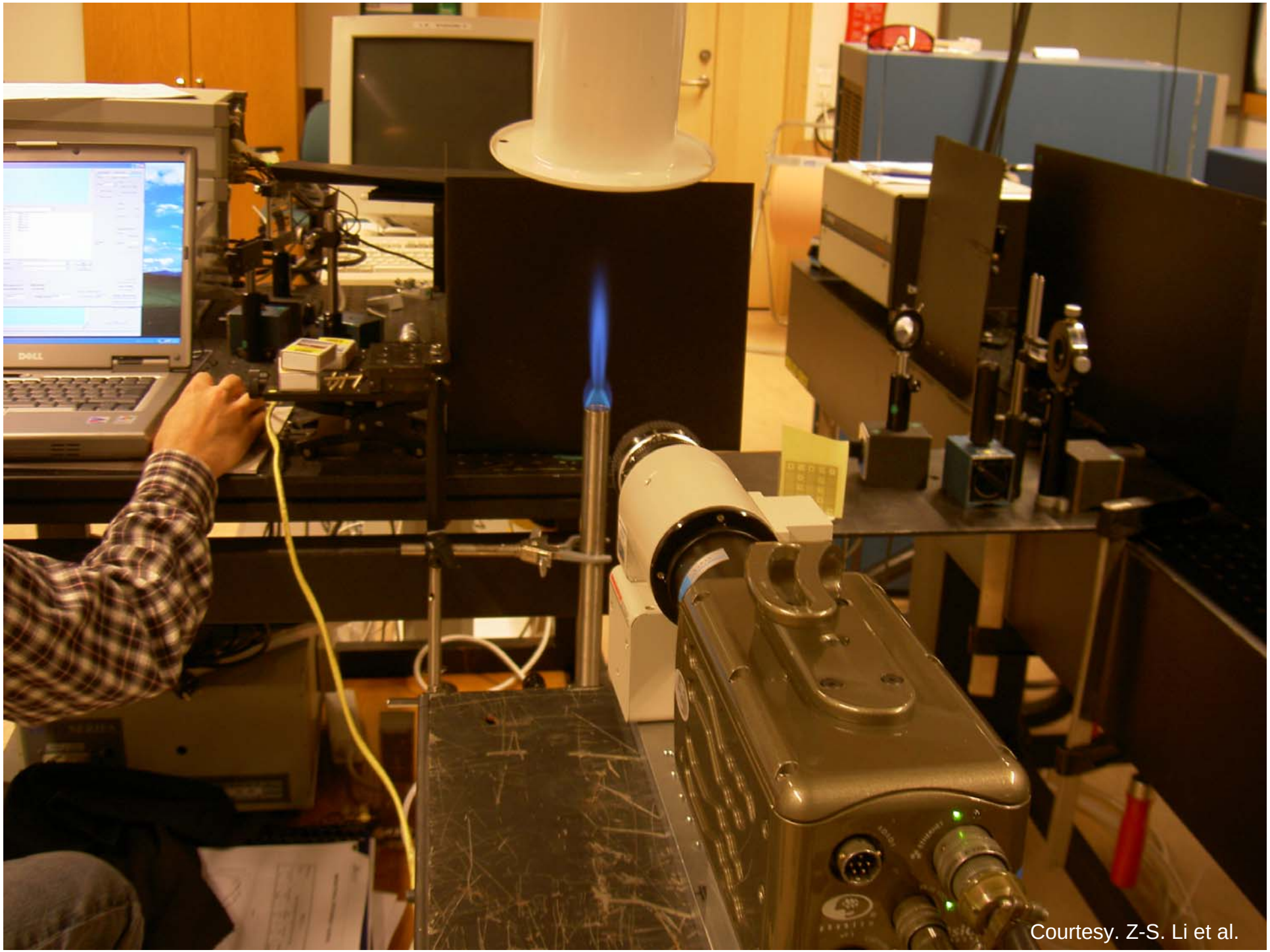


General features:

- High sensitivity
- 2D imaging capabilities
- Spontaneous technique
- Measures temp. and konc.
- Quantification problem

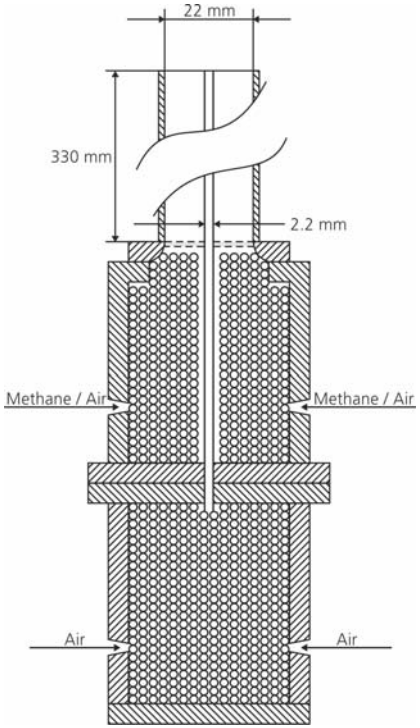
Two-dimensional measurements

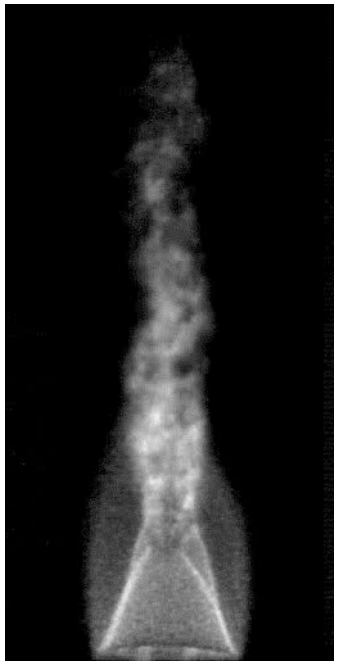


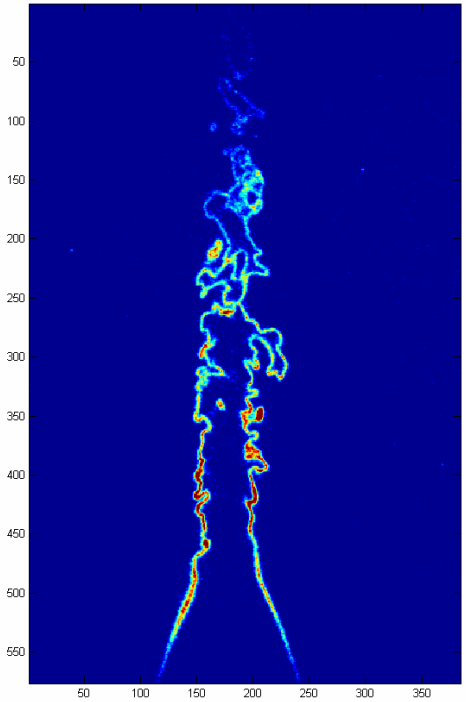


Courtesy. Z-S. Li et al.

Turbulent jet flame







Vi = 105 m/s (air)

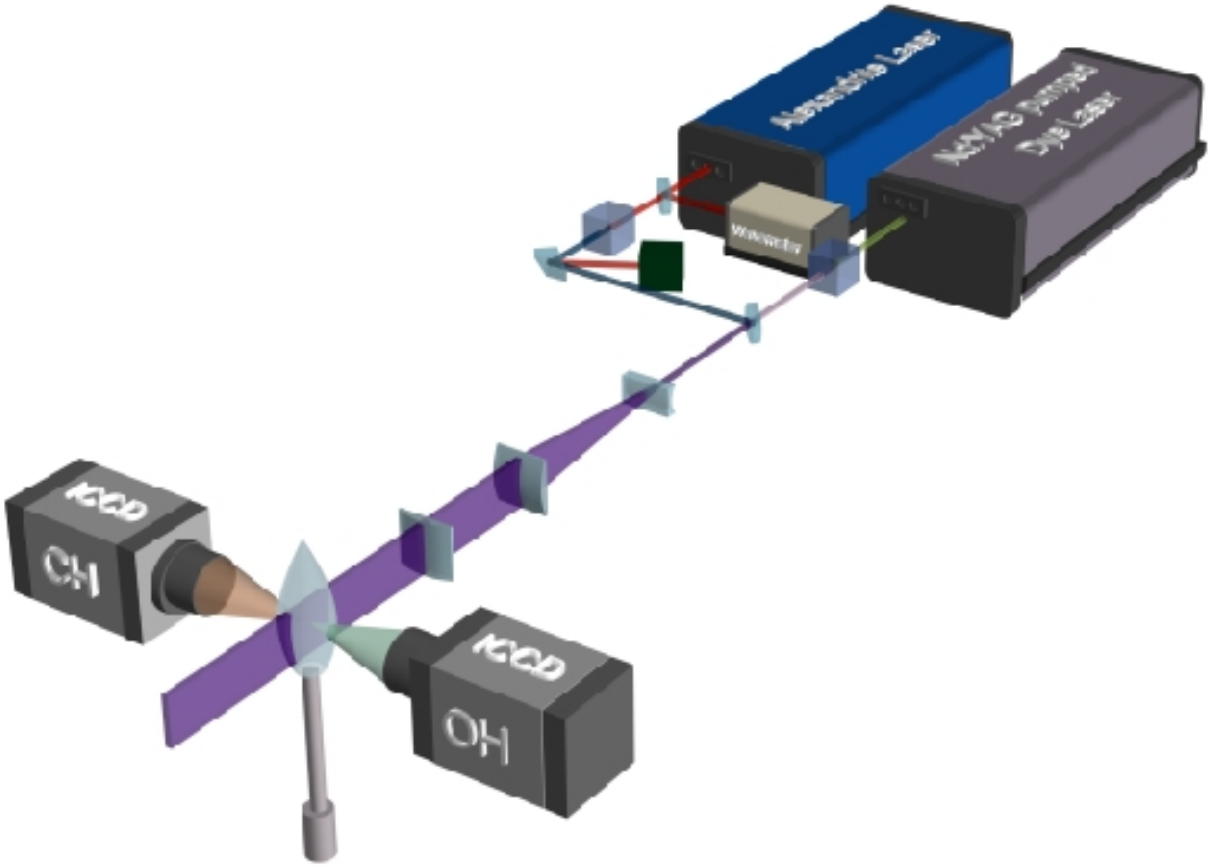
Exposure time = 2 μs

14000 frames/s

CH LIF

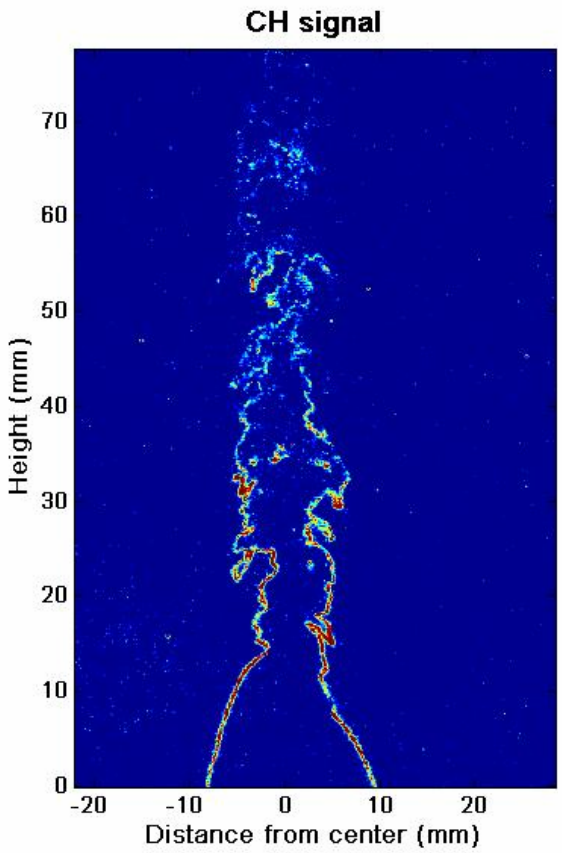
Courtesy. Z-S. Li et al.

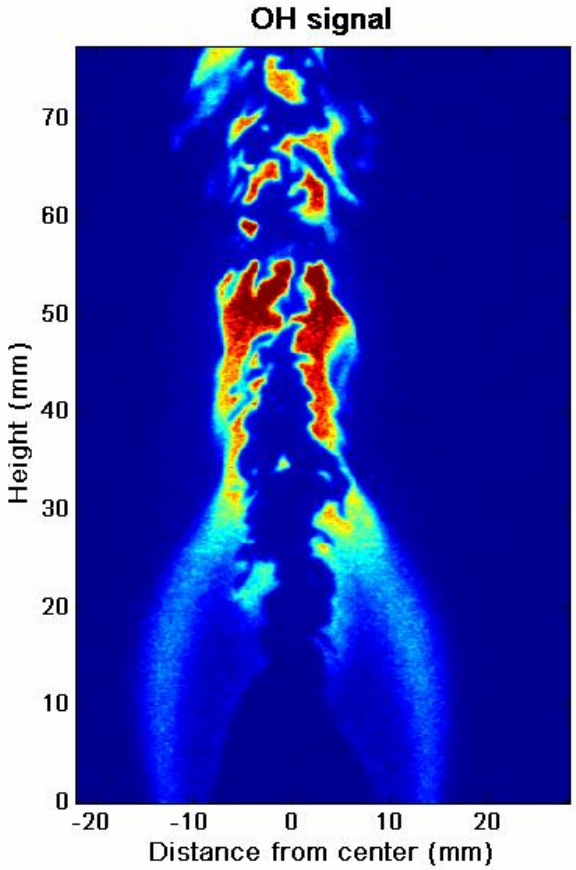
CH/OH



The experimental setup for simultaneous PLIF of OH and CH in turbulent premixed jet methane/air flames

Simultaneously CH/OH visualization (jet flame)

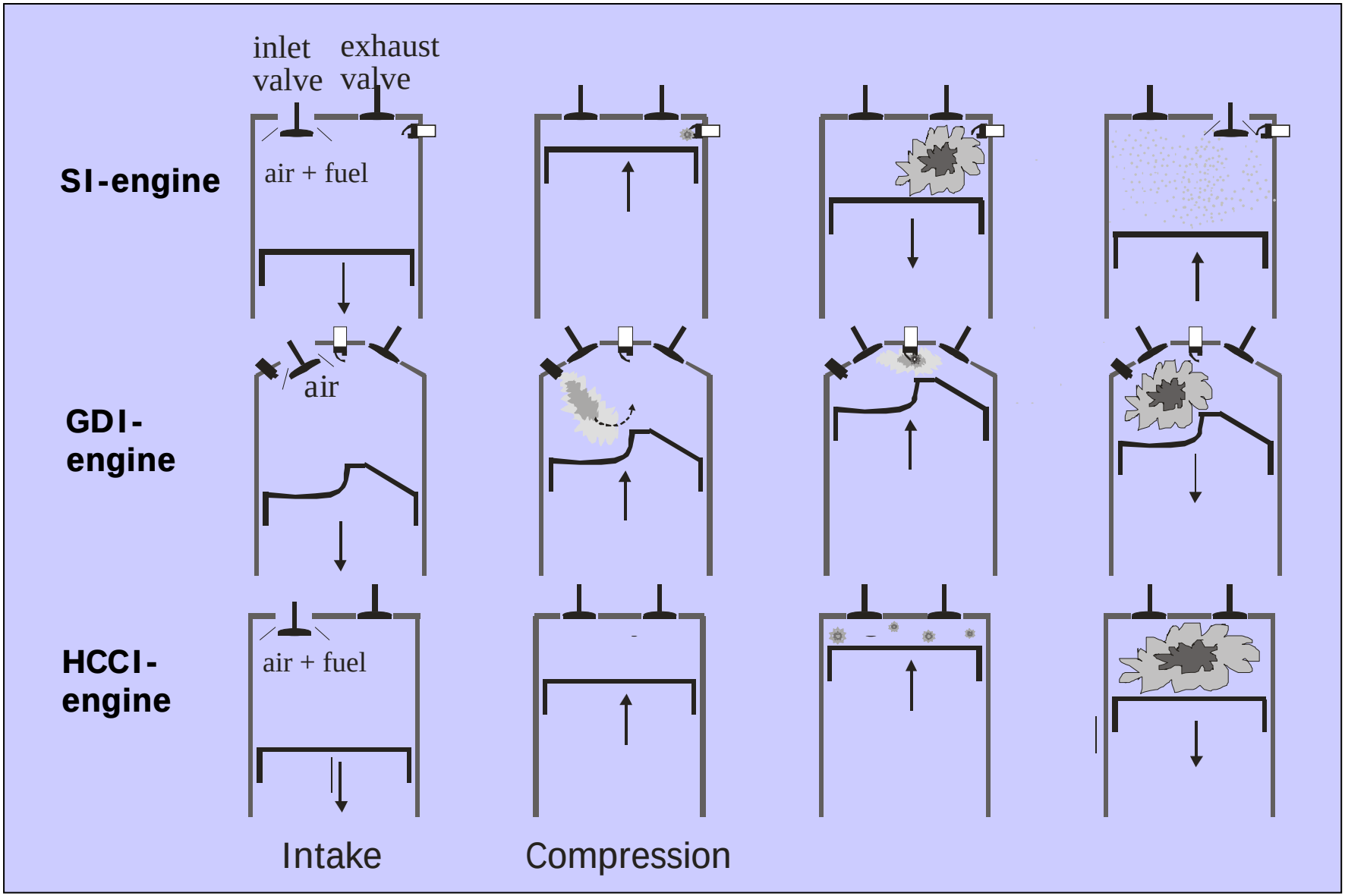




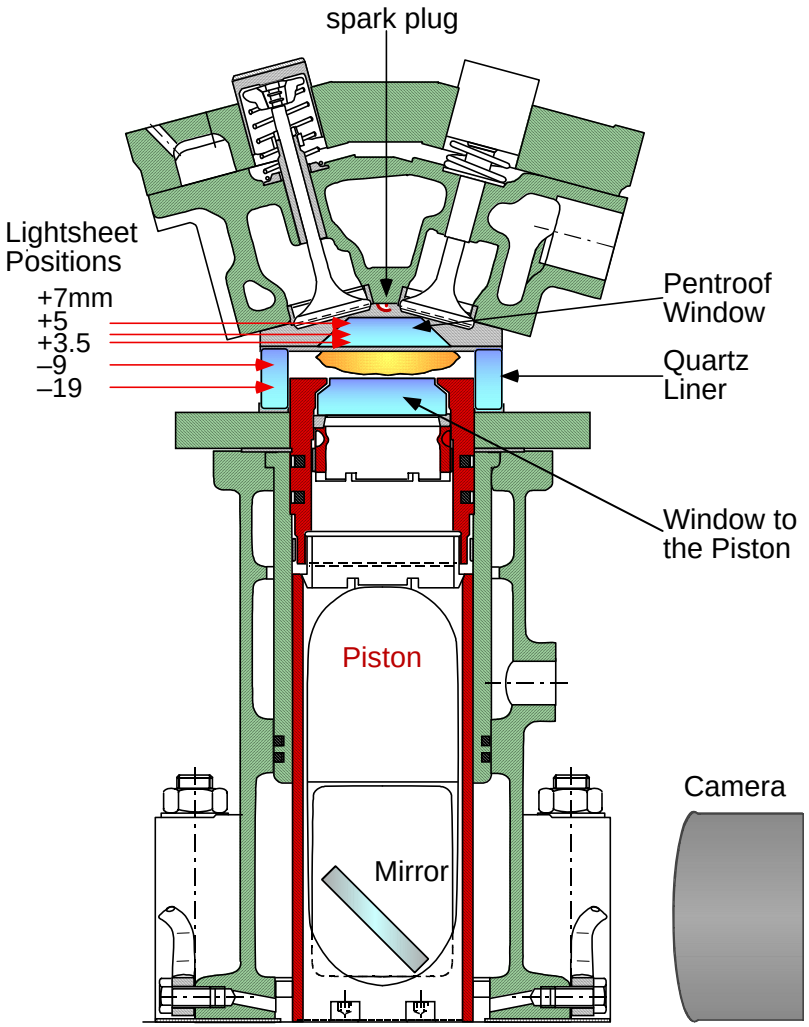
Courtesy: Z-S. Li et al.

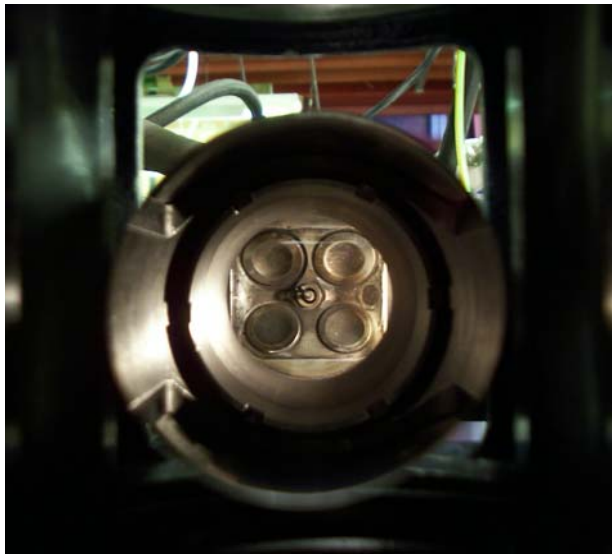
LIF visualization
a) Engine environments

Engine types



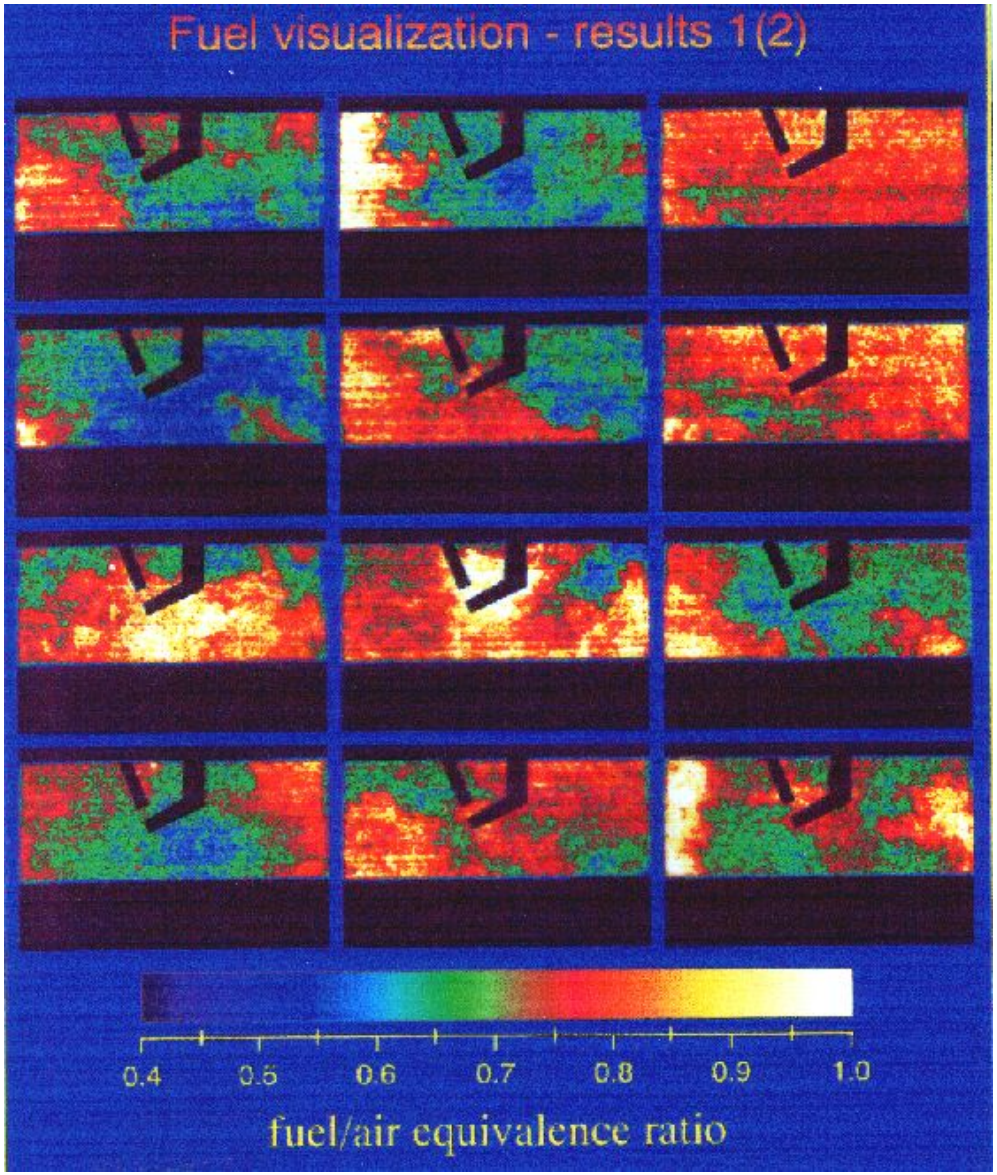
Engine optical access



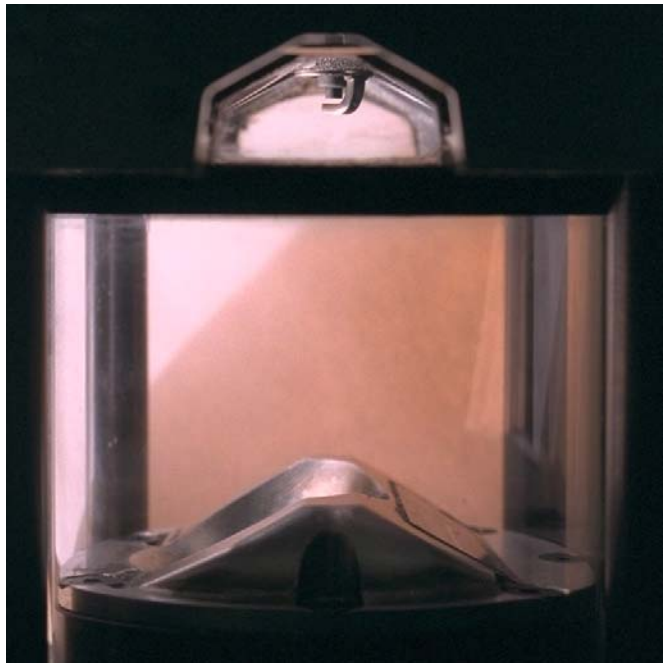


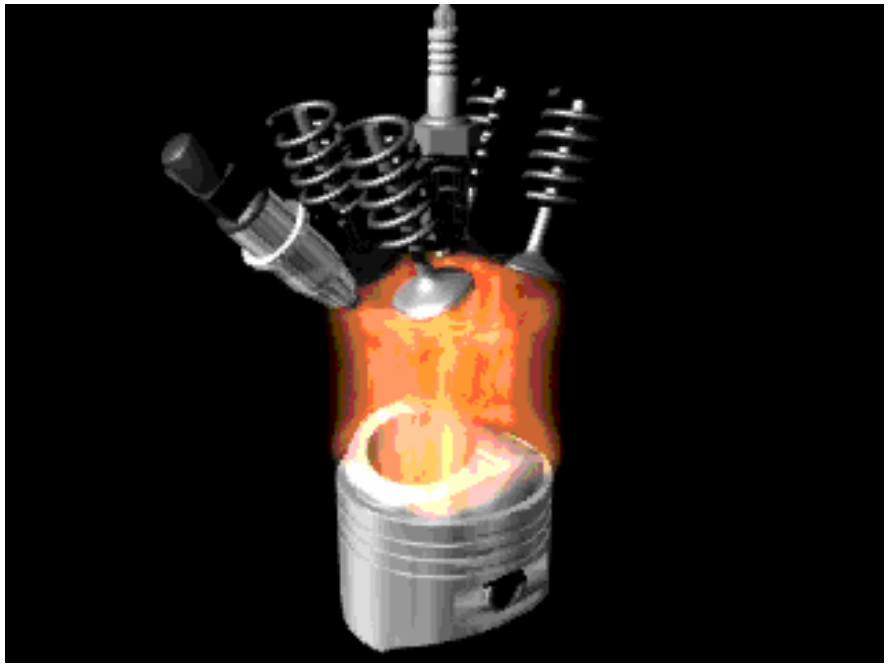
Fuel visualization

Twelve fuel/air calibrated single shot registrations in an engine using 2D LIF with 3-pentanone seeded to iso-octane. This shows the cyclic variations in the engine.

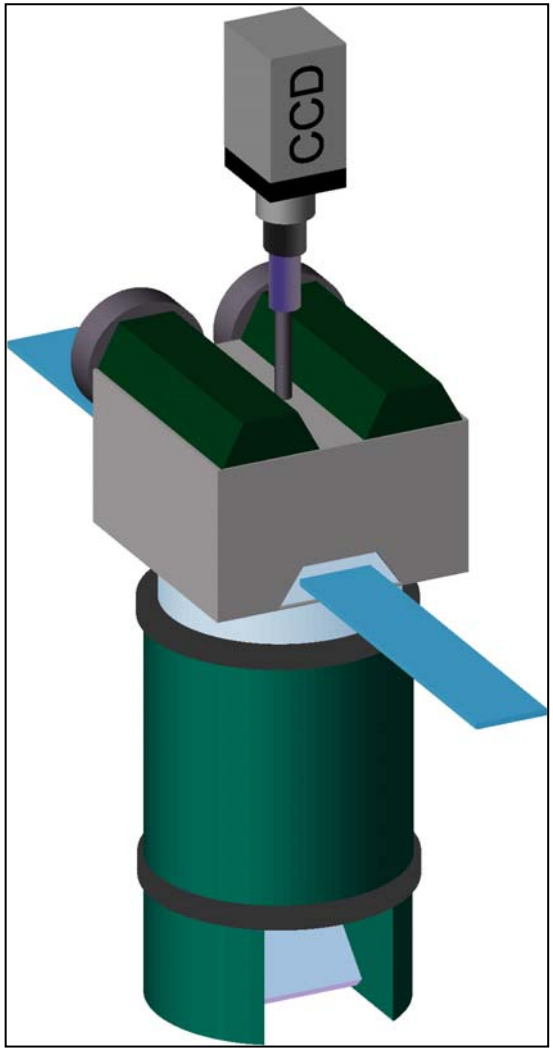


Direct Injection Stratified Charge (DISI) Engine





In-situ engine measurements with limited optical access

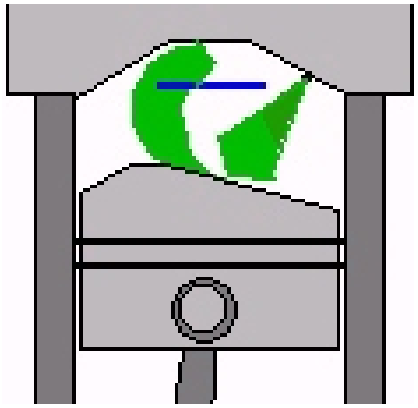


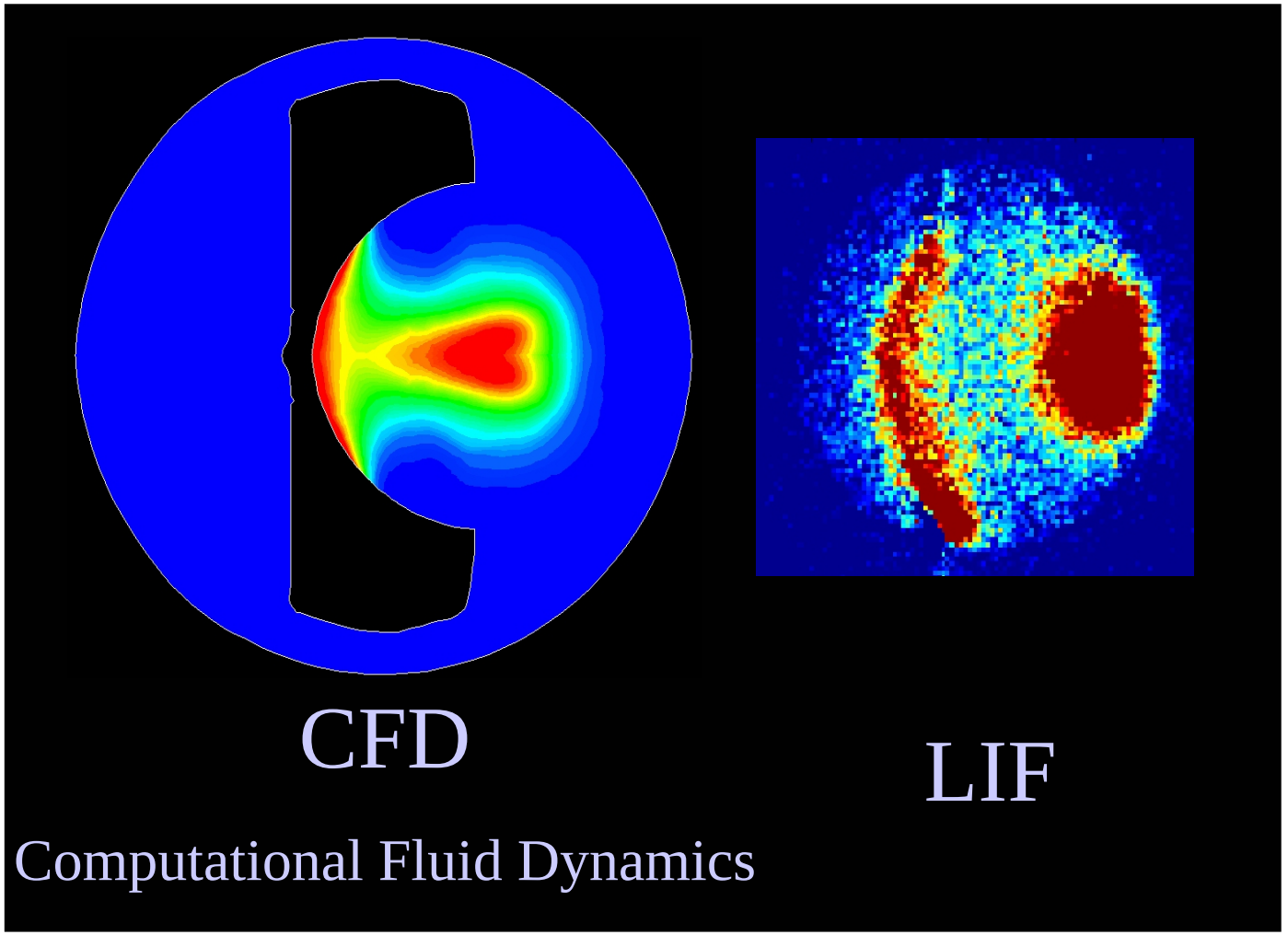
Endoscopic LIF Detection System for in-situ DISI engine visualization

- A standard Karl Stortz endoscope was inserted in the sparkplug hole.
- The endoscope was coupled to an image intensified CCD camera by a single 25 mm positive lens.

Fuel visualization through endoscope:

Comparison between LIF and CFD





Simultaneous detection of formaldehyde and OH

- **Formaldehyde**

  Excitation at 355nm

  Detection: >400nm

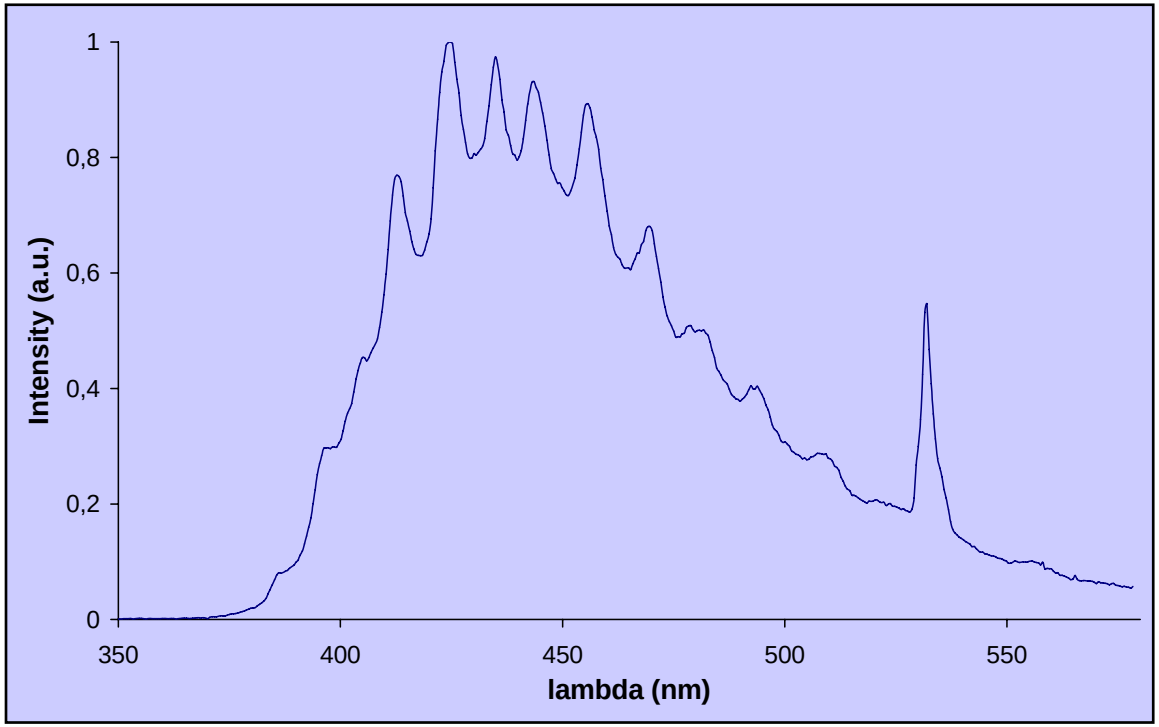
- **OH**

  Excitation at 283nm

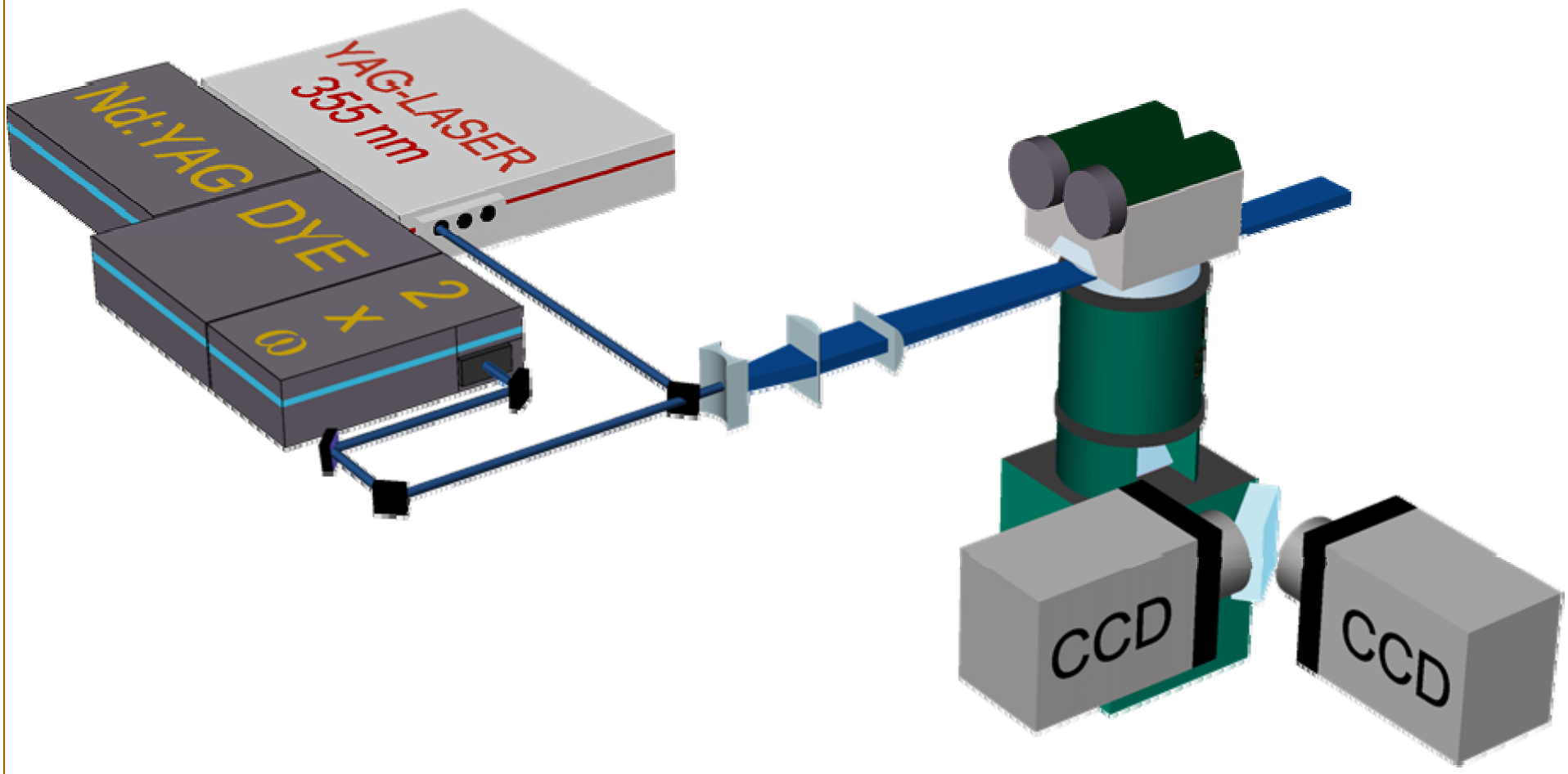
  Detection at 308 nm

Delay between the two lasers: 500ns

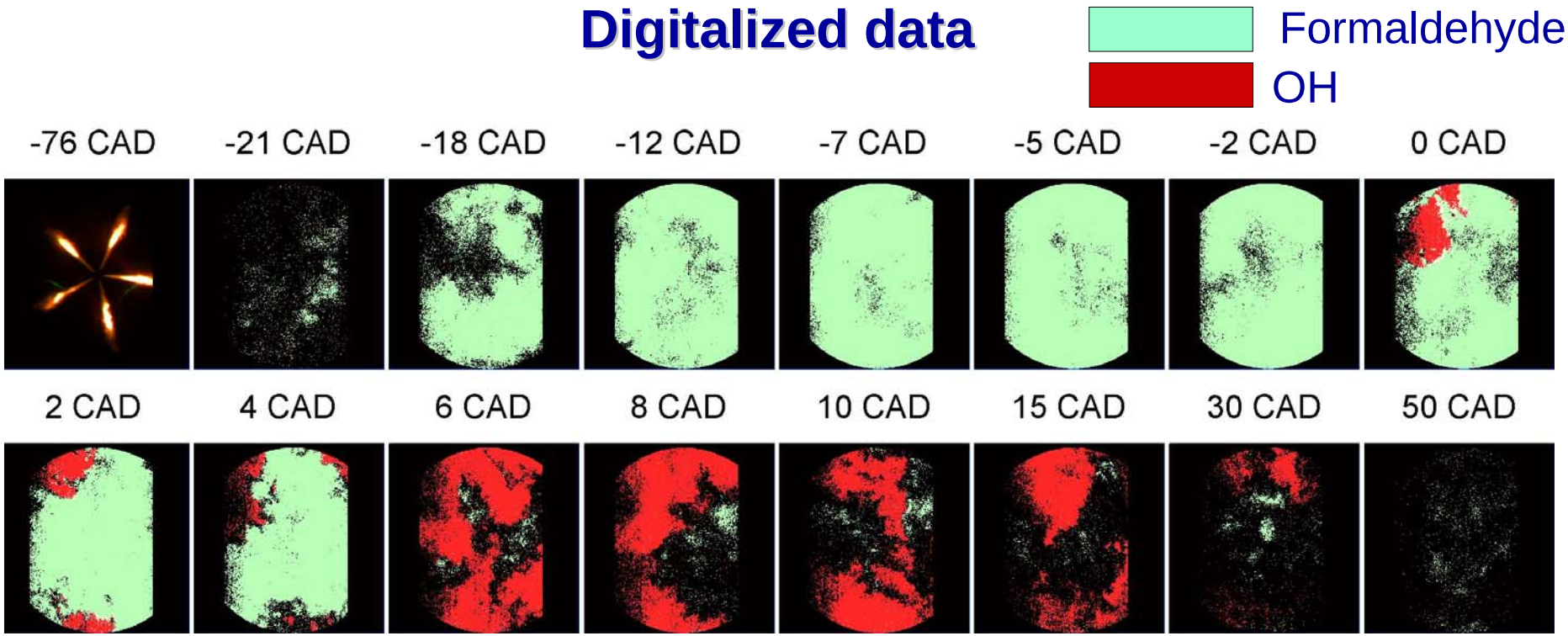
(0.004 CAD @ 1200 rpm)



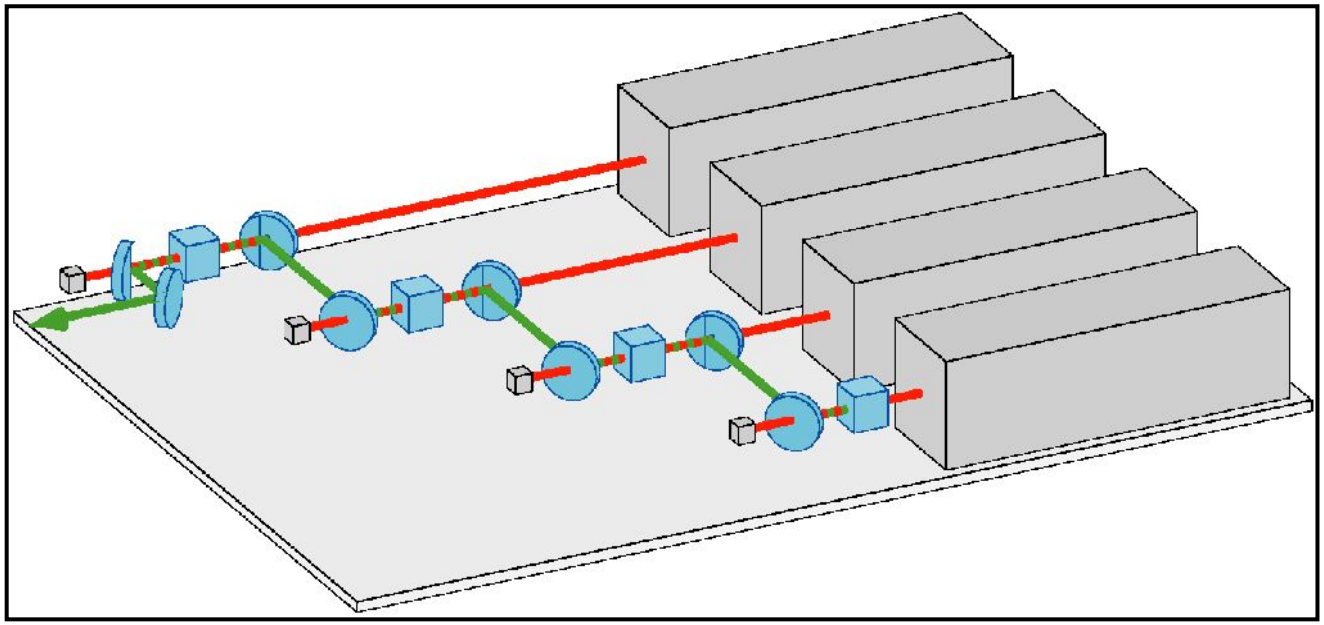
Experimental setup

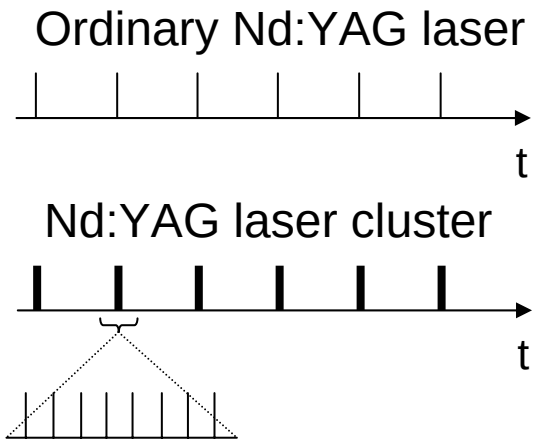


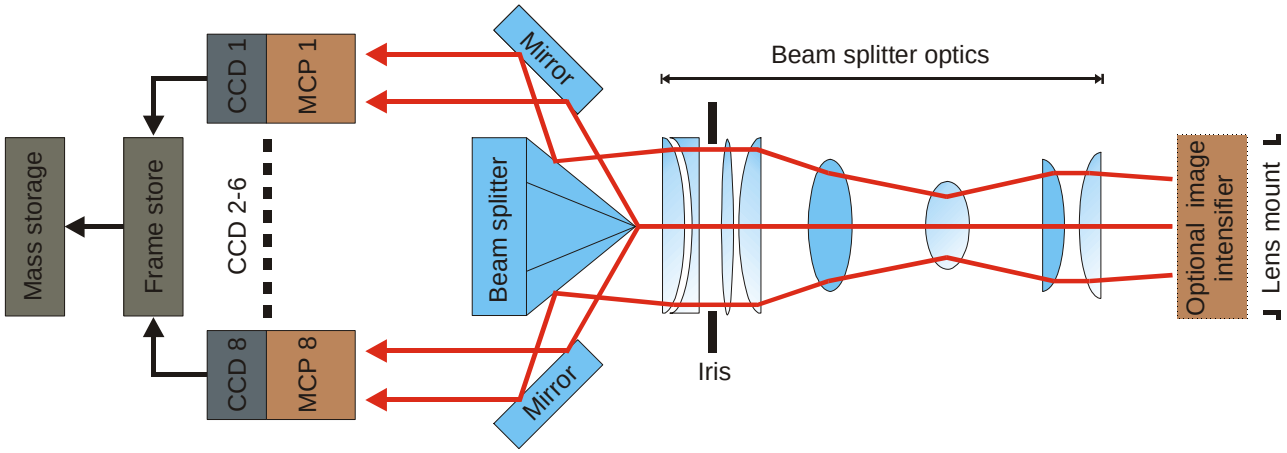
Formaldehyde and OH distributions in a DI HCCI engine



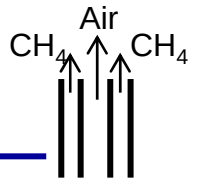
High speed LIF system

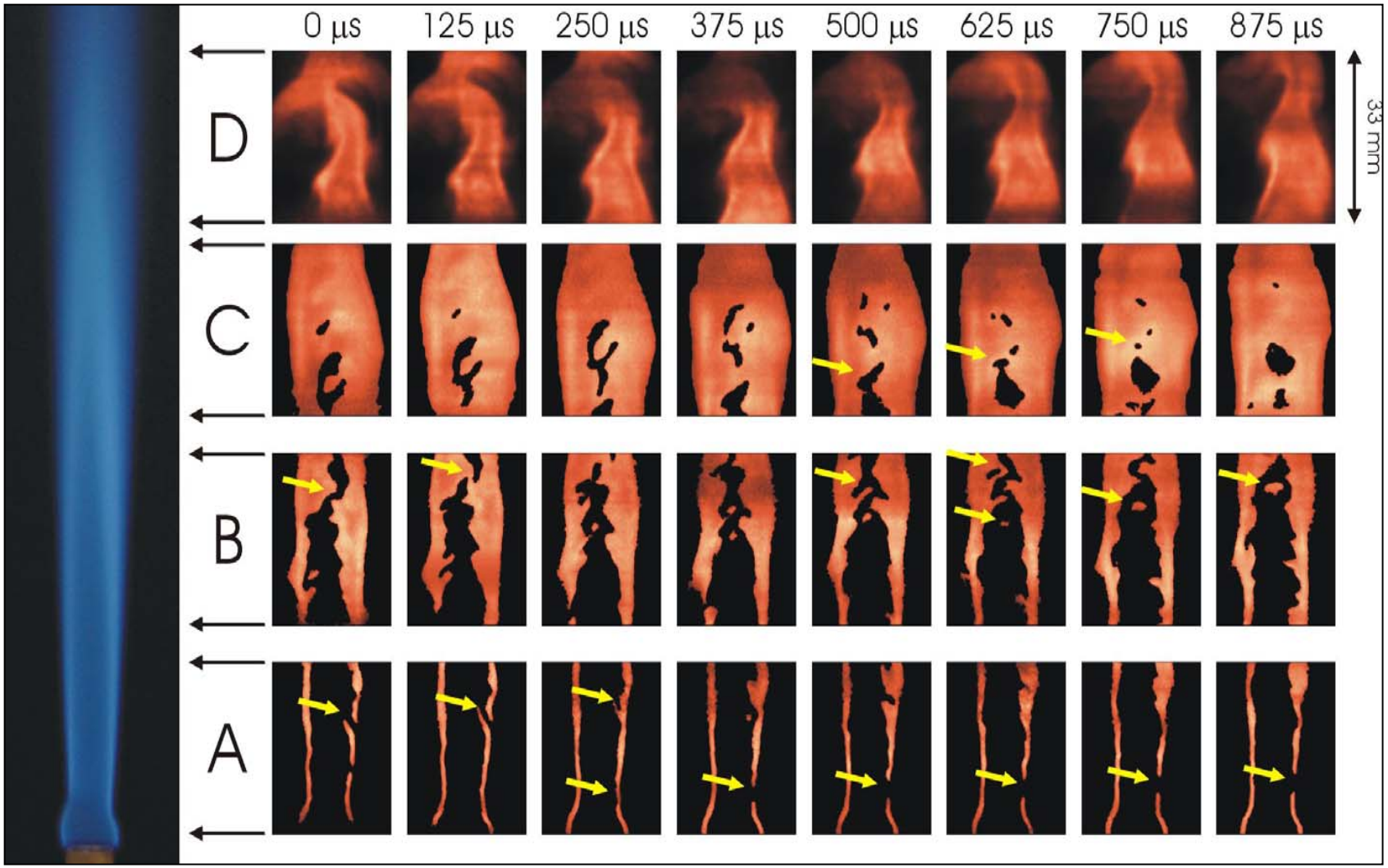






Turbulent non-premixed CH_4/air flame, Re=5500

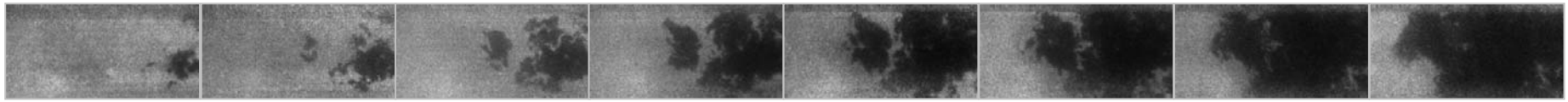


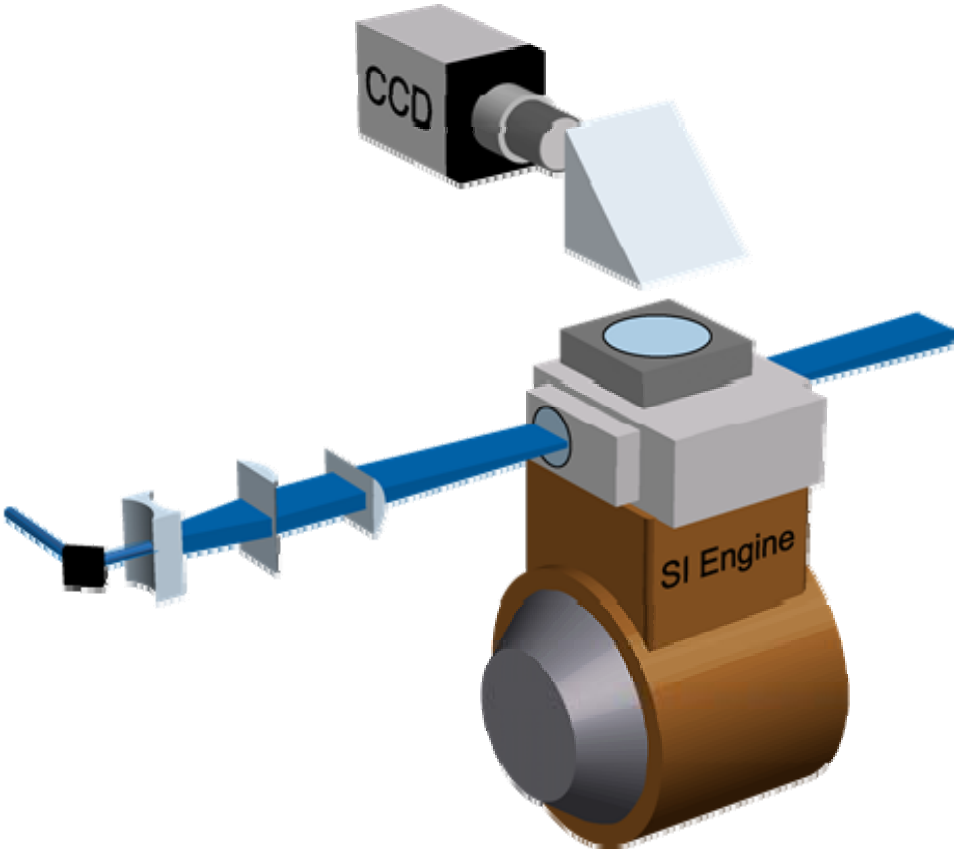


Fuel Tracer PLIF in an SI-engine

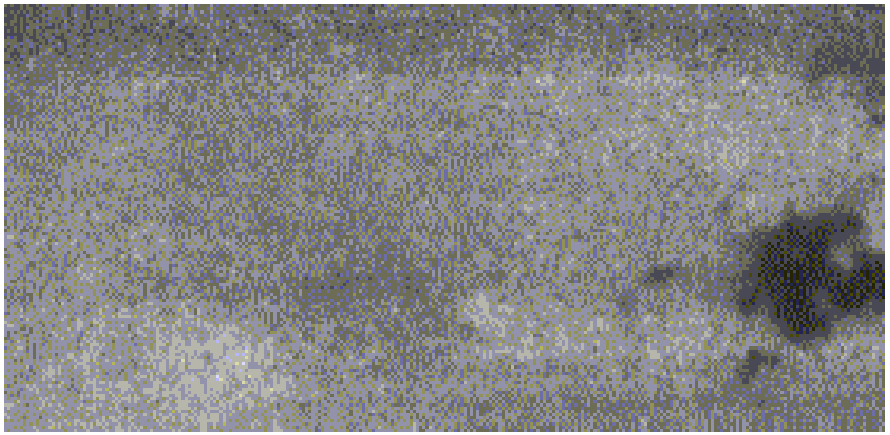
(single-cycle-resolved)

7 ATDC 7.75 ATDC 8.5 ATDC 9.25 ATDC 10 ATDC 10.75 ATDC 11.5 ATDC 12,25 ATDC



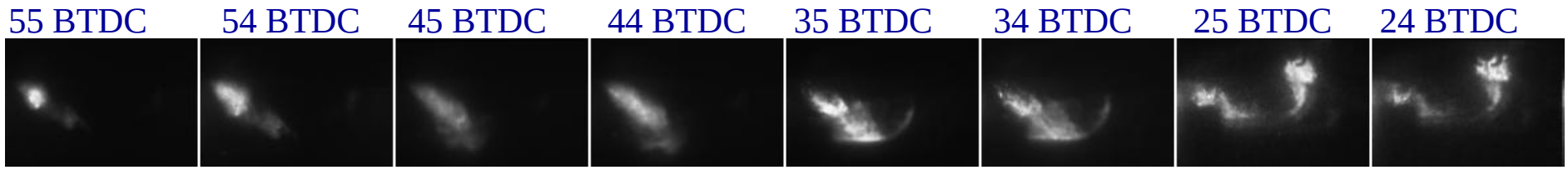


- Fuel: iso-octane
- Tracer: 6% 3-pentanone

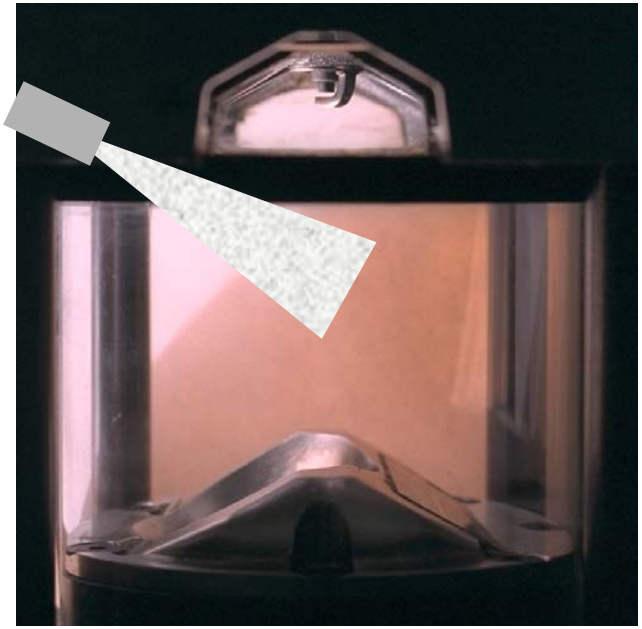


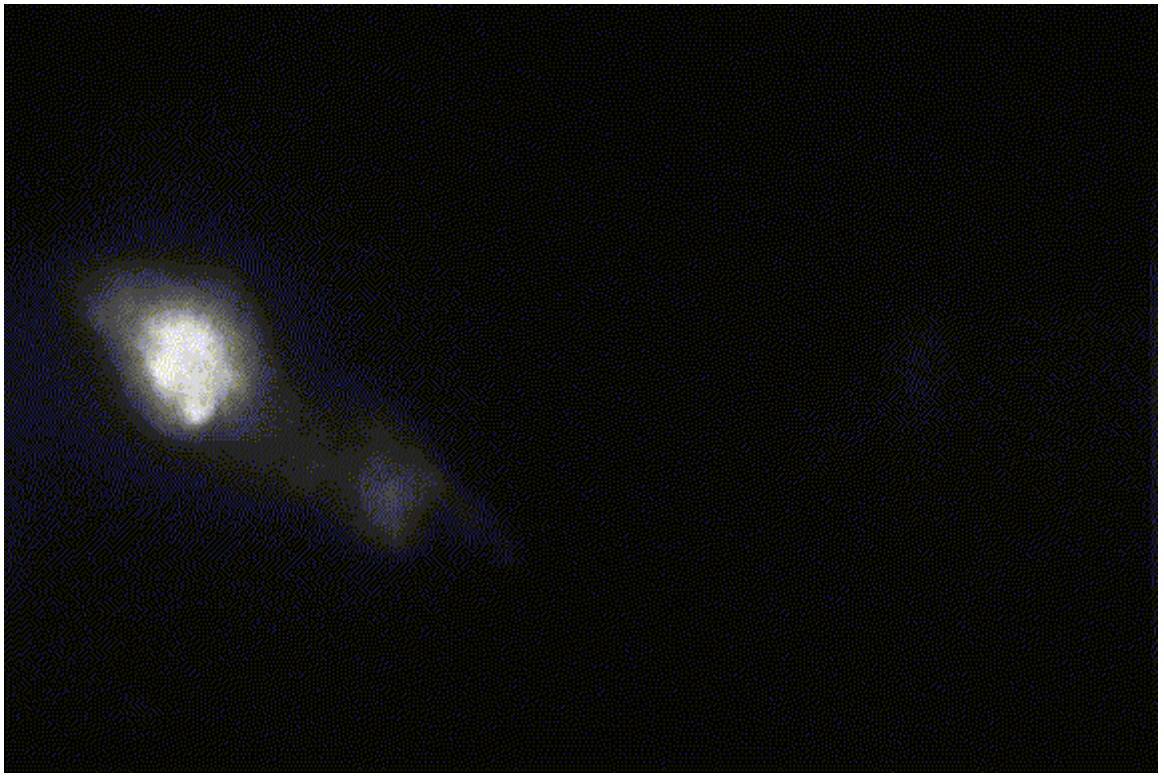
Fuel Tracer PLIF in a DISI-engine

(single-cycle-resolved)



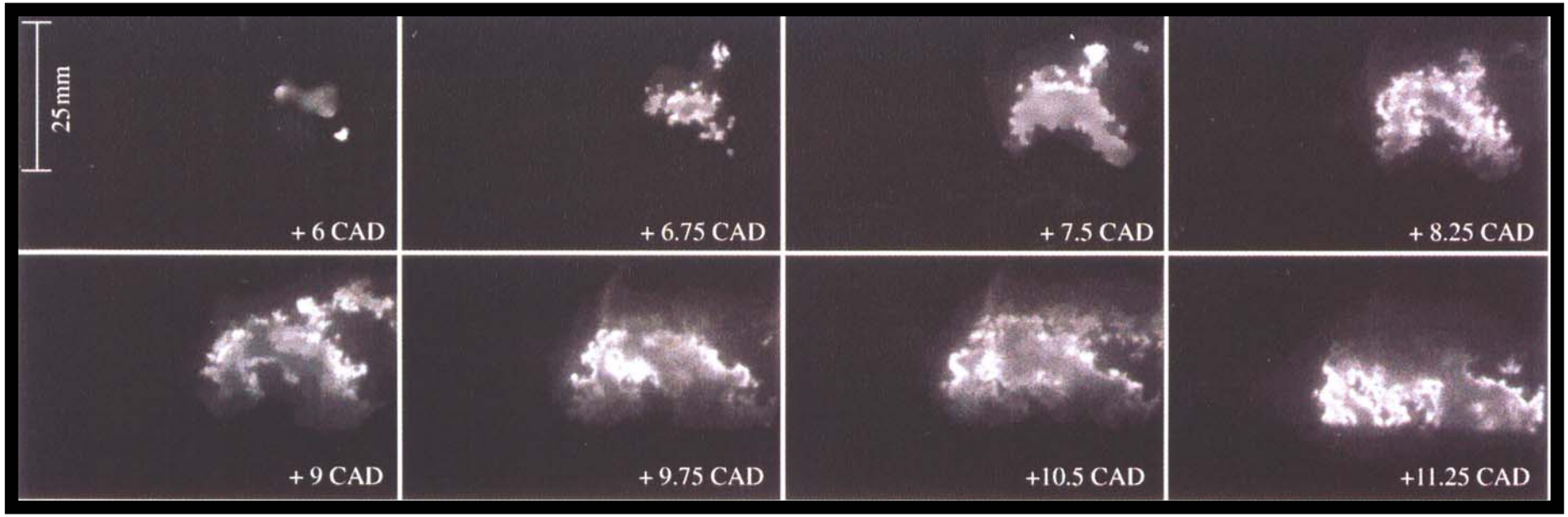
- SOI 64 CAD BTDC





OH PLIF in a SI engine

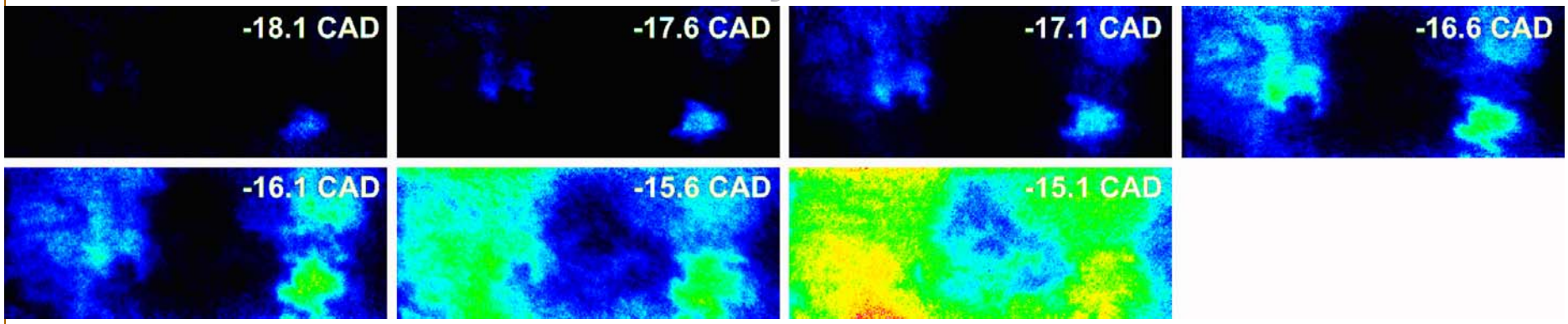
(resolved single-cycle)



$\Delta t = 100\ \mu s$

Cycle-resolved formaldehyde visualization in a HCCI engine

Formaldehyde formation

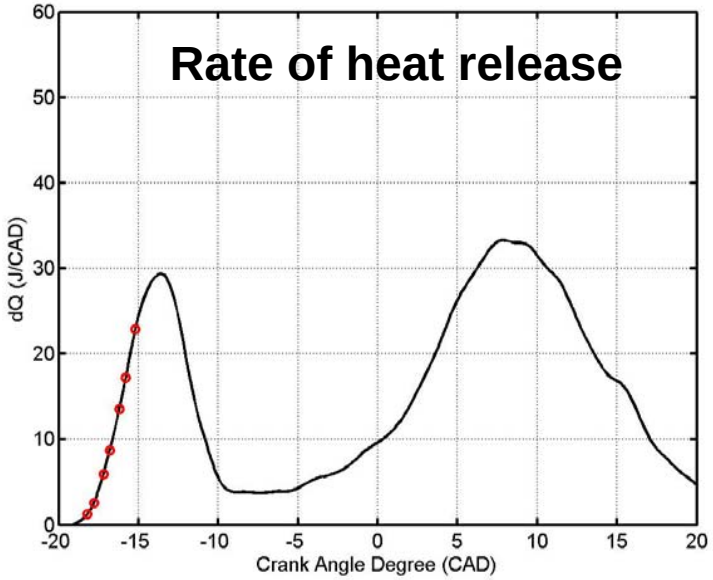


Time-separation 0.5 CAD

45 mJ/pulse at 355 nm

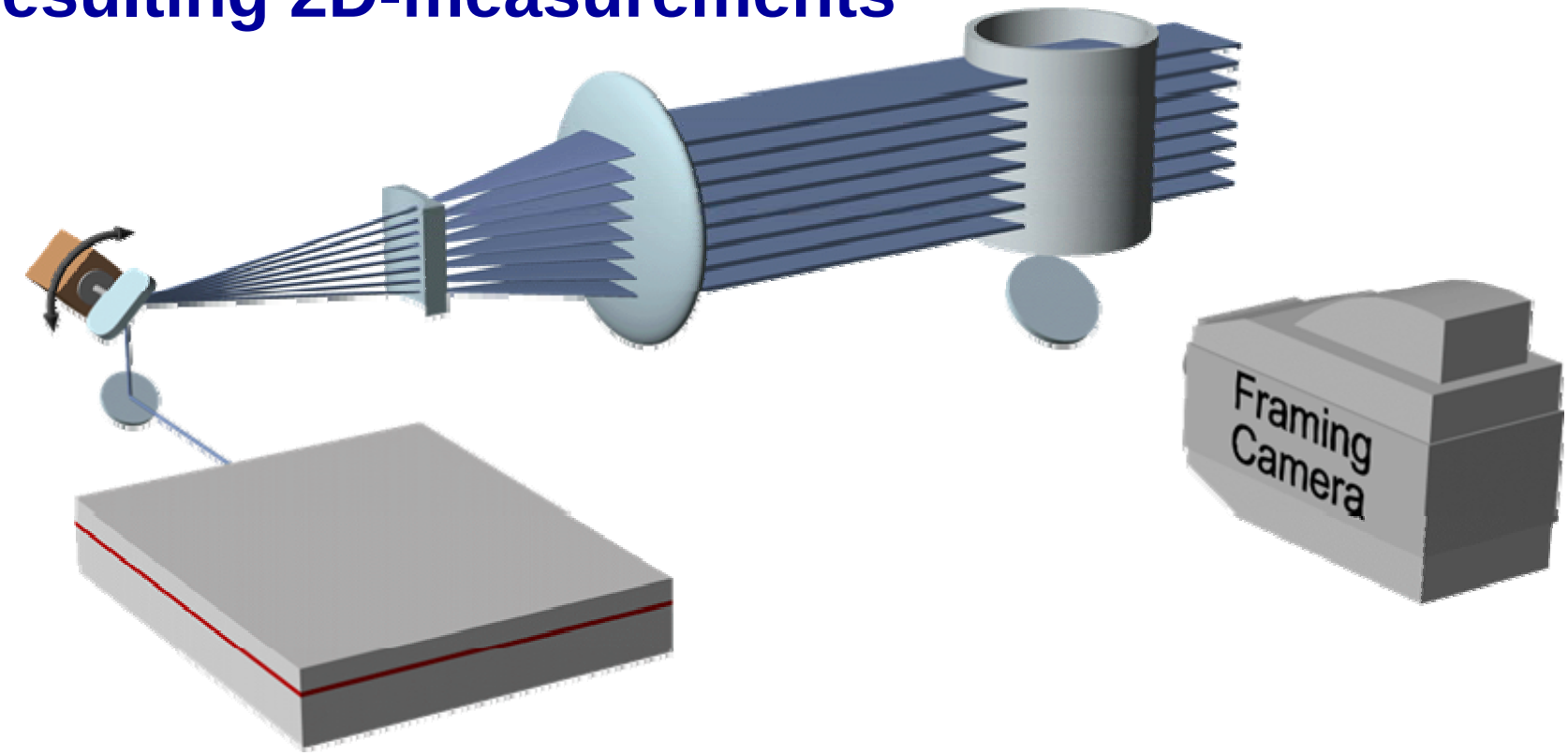
Intensifier gate time 50 ns

λ= 4.5



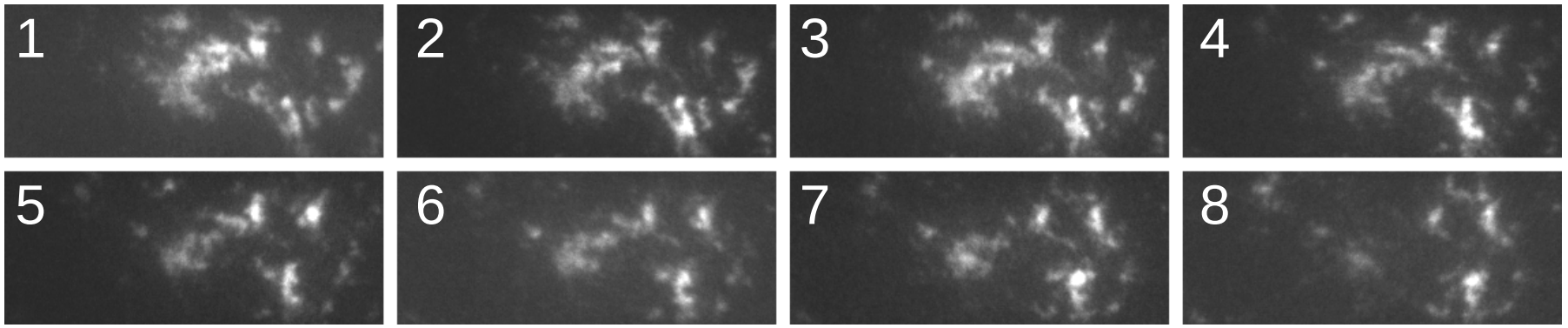
3-D fuel tracer PLIF

- Information on “flame” topology
- Rapid slicing of the measurement volume
- 3D data reconstructed from the eight resulting 2D-measurements

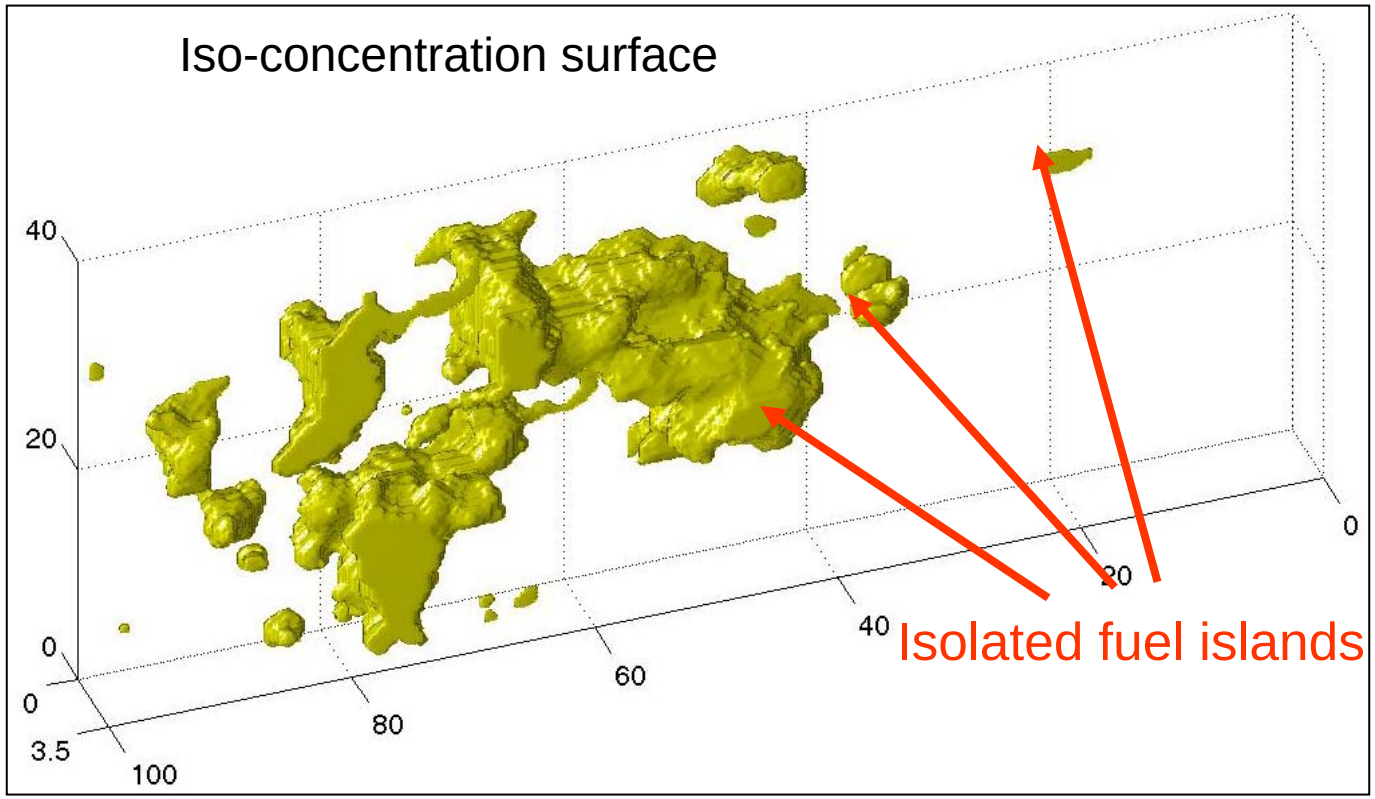


+6 CAD

3-D fuel tracer PLIF in an engine



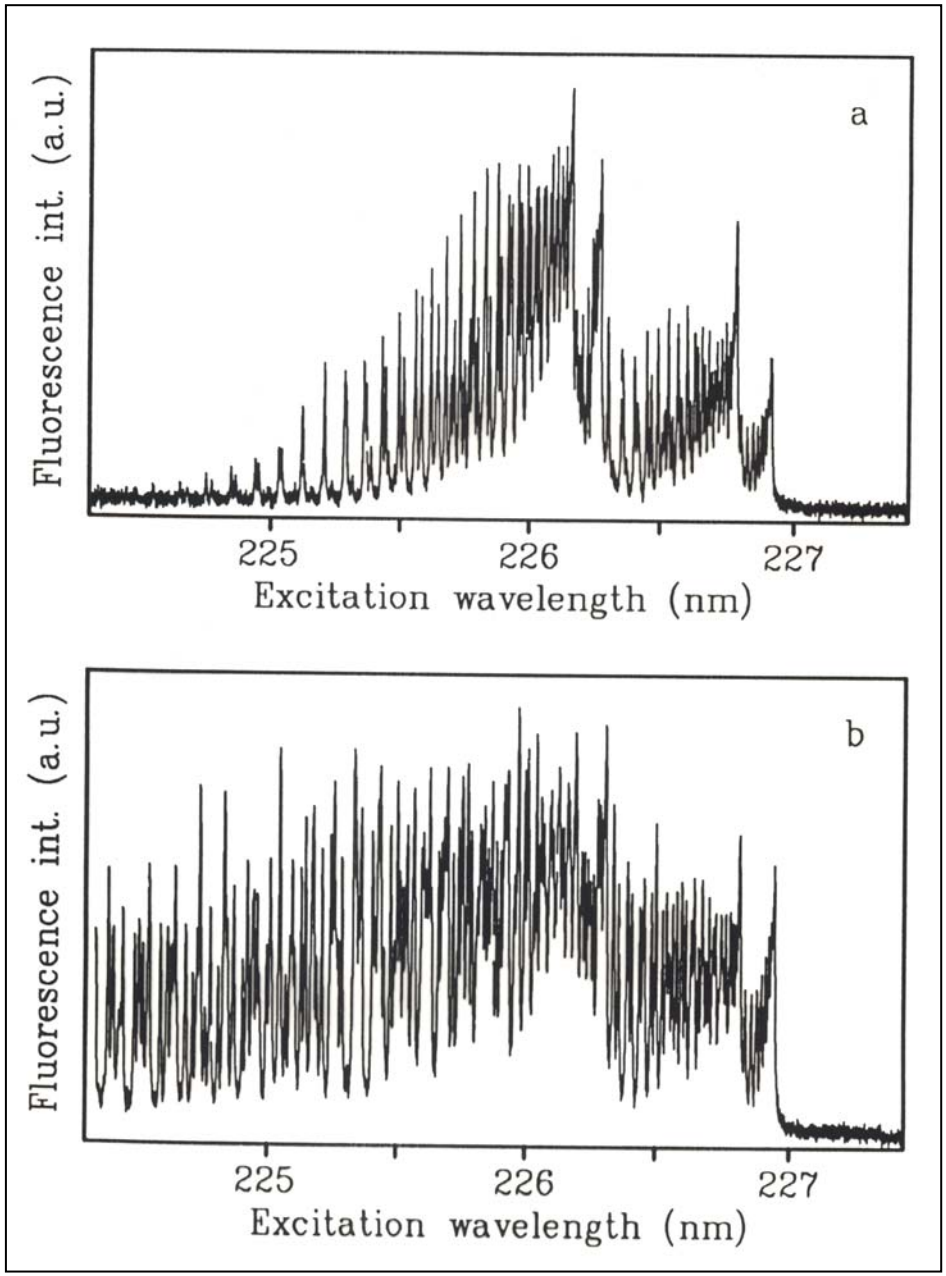
Sheet spacing: 0.5 mm



Temperature measurements

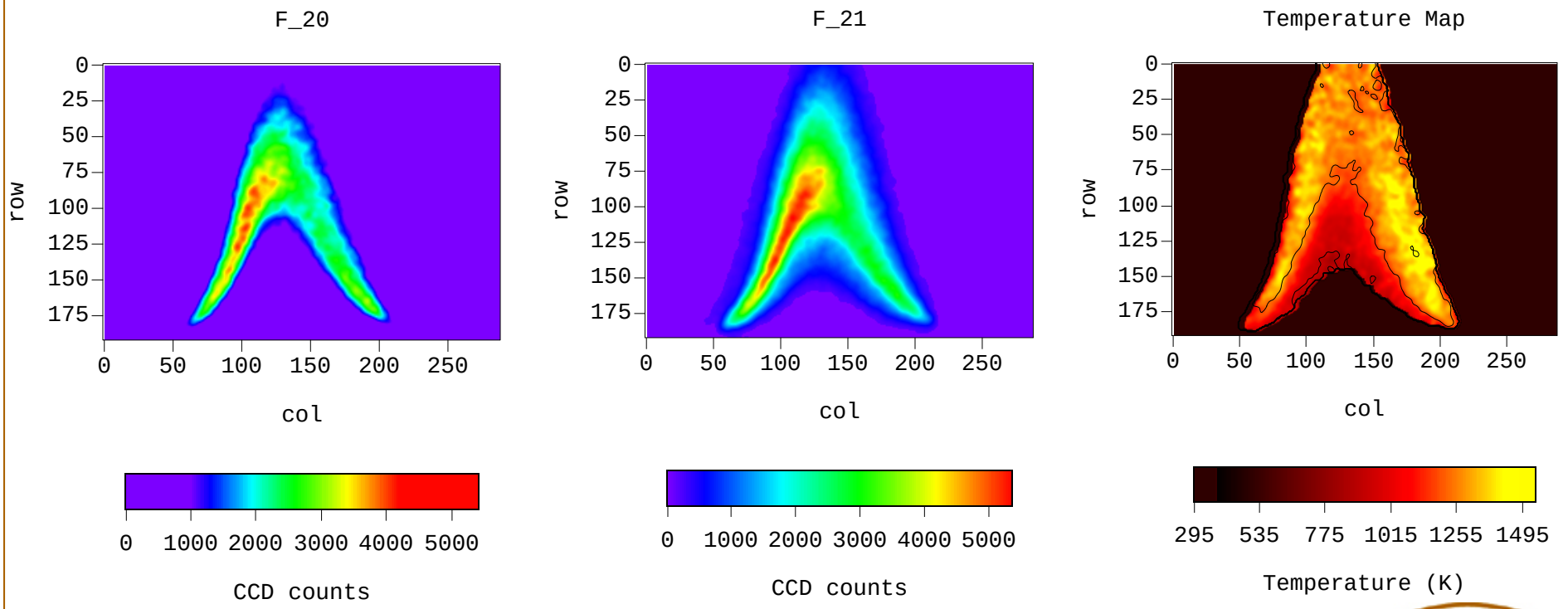
Laser-induced excitation spectra of NO;

a) 300K, b) flame temp.

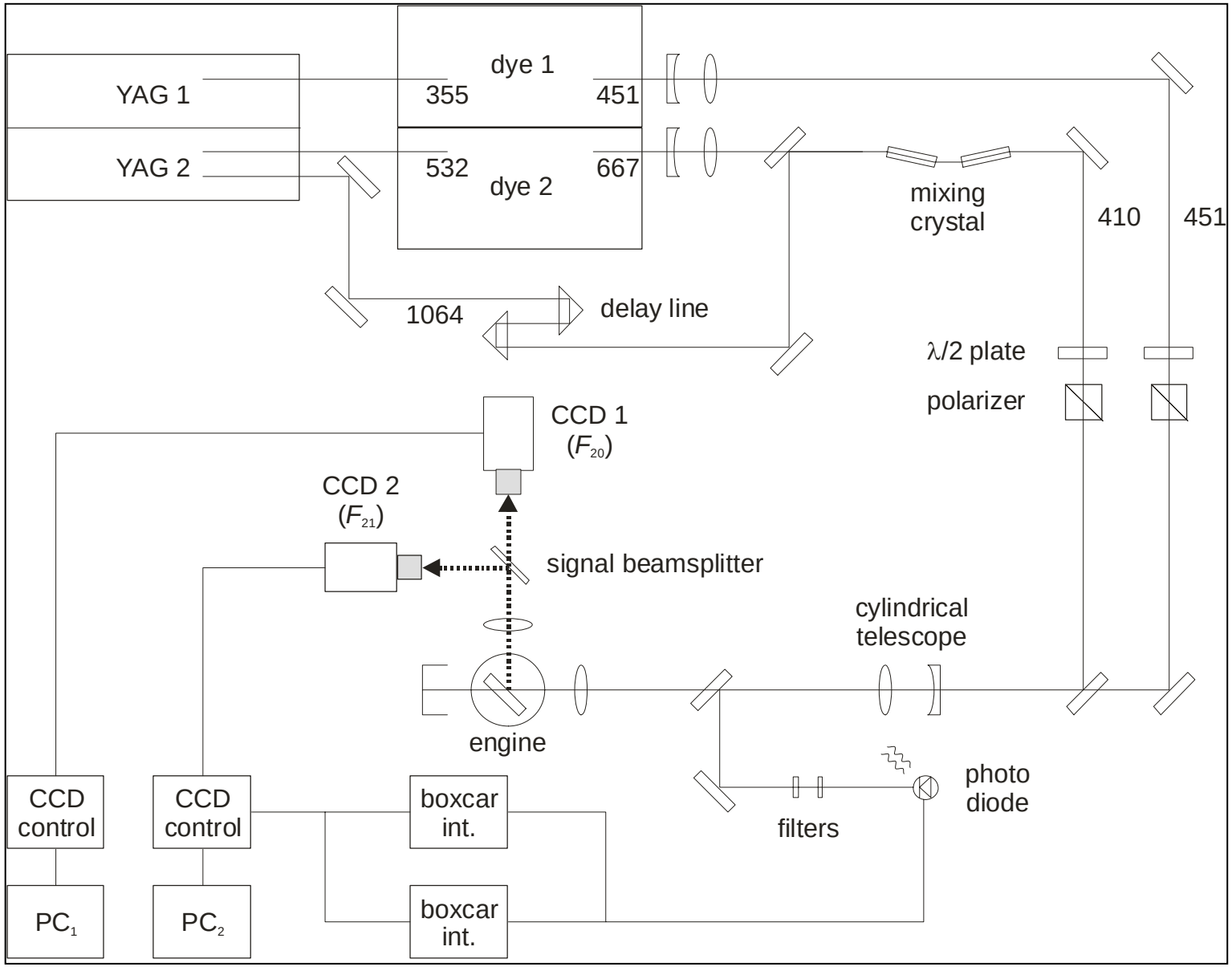


Principle 2D temperature imaging:

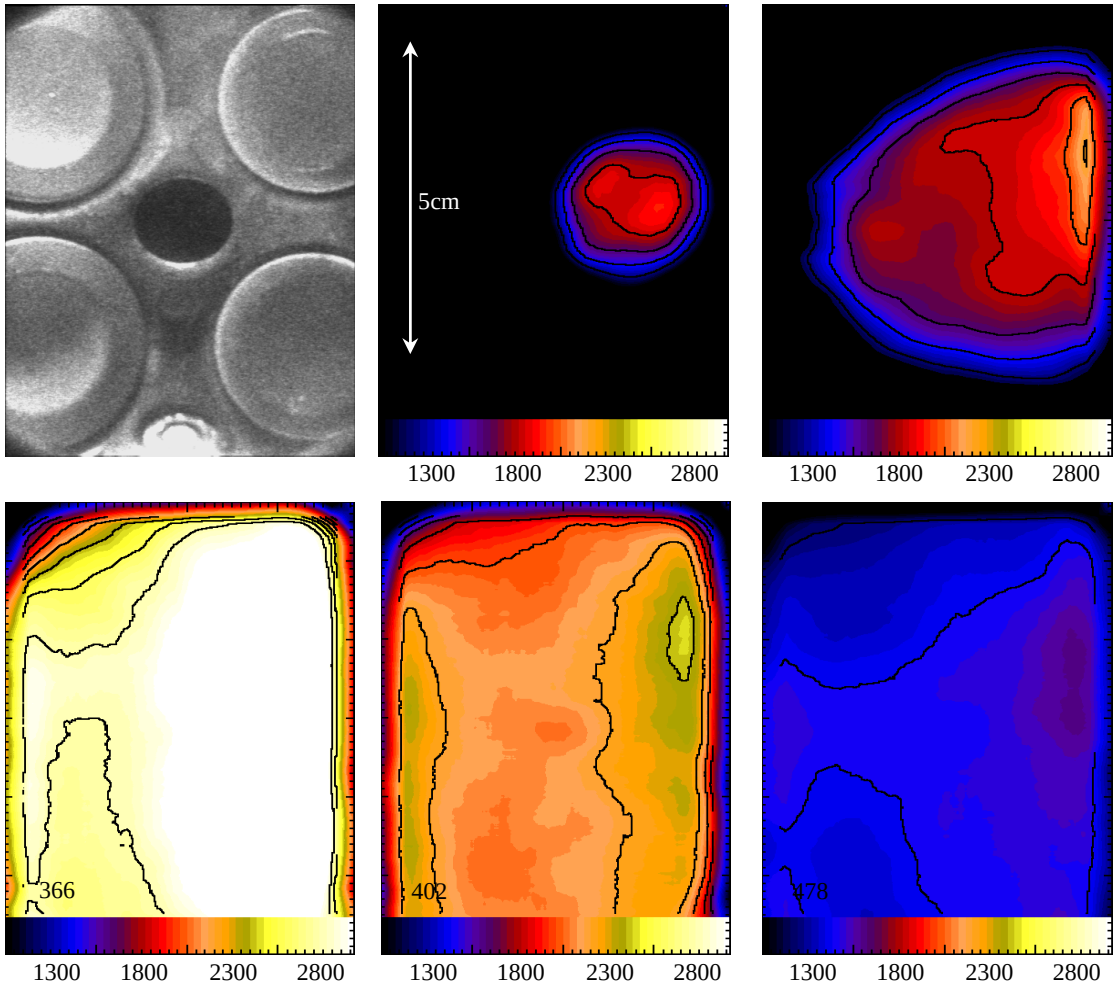
TLAF



Experimental set-up: TLAF



Single shot T-distributions in an engine



LIF visualization
a) Gasturbine environments

Experimental set-up at

ABB-STAL

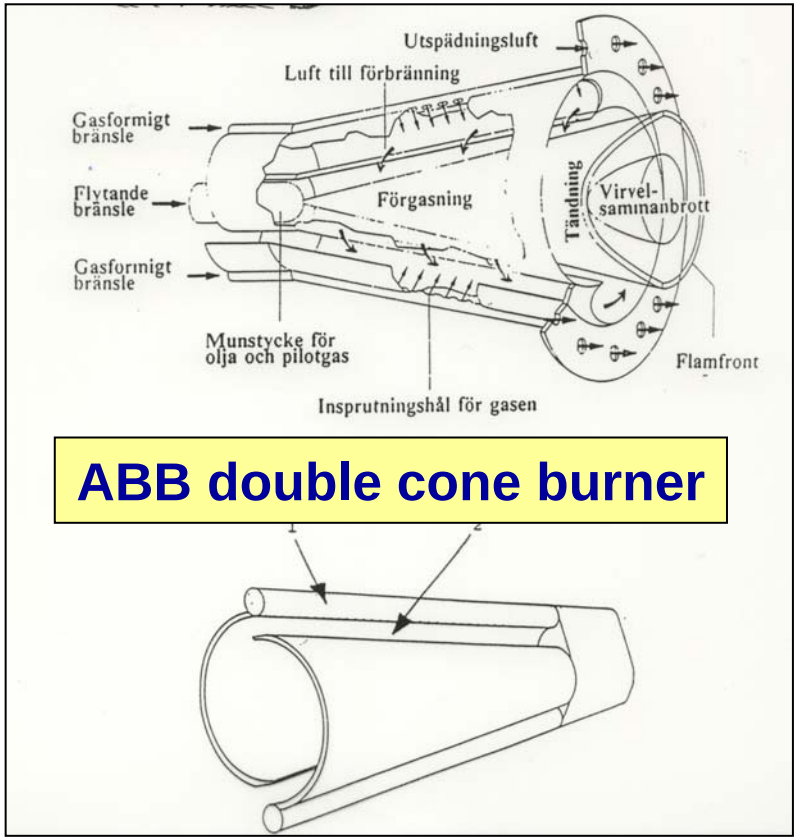
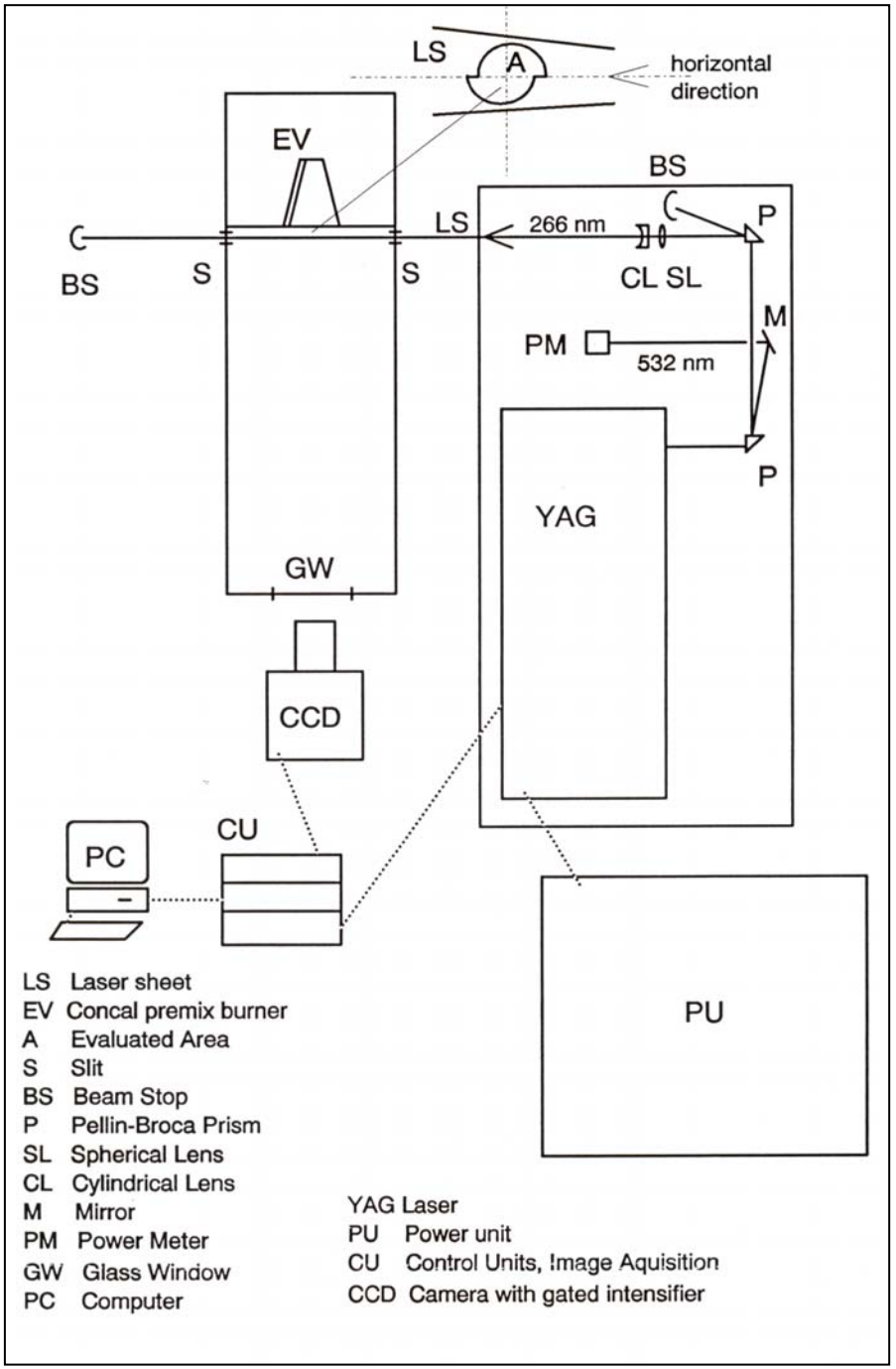
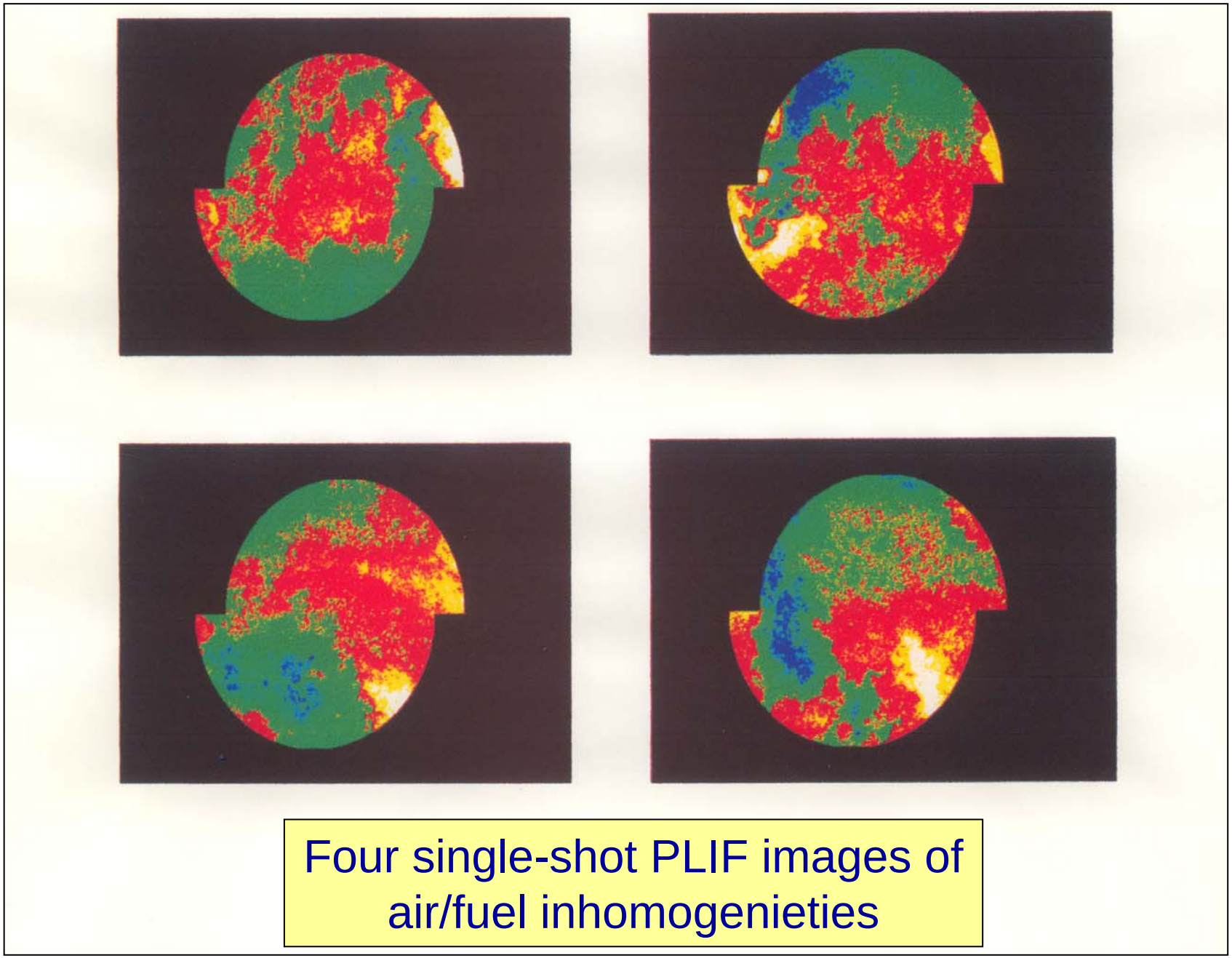


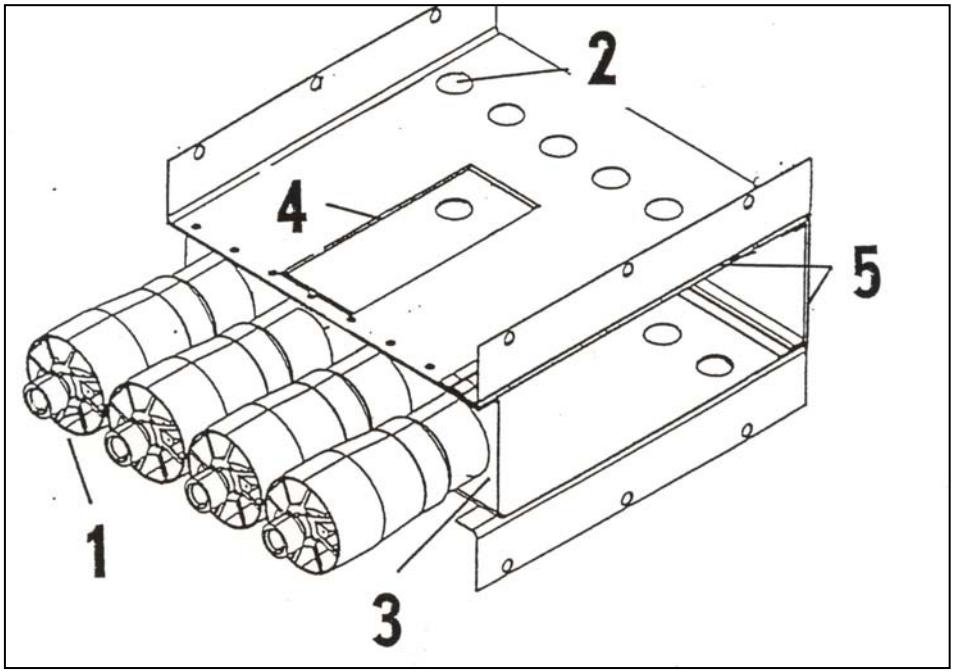
ABB double cone burner

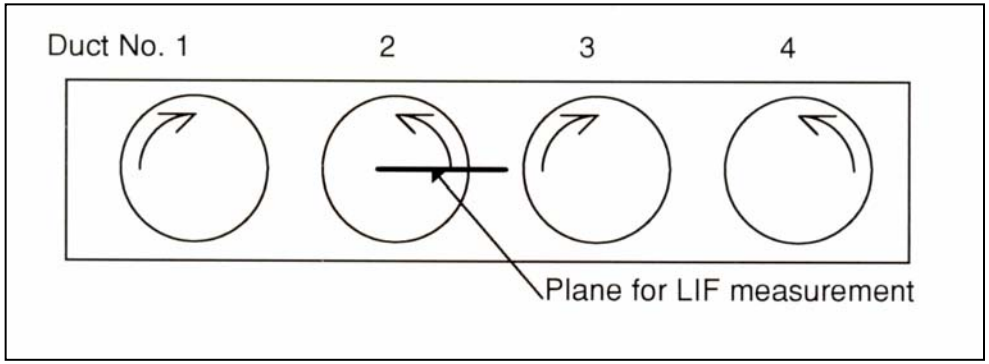


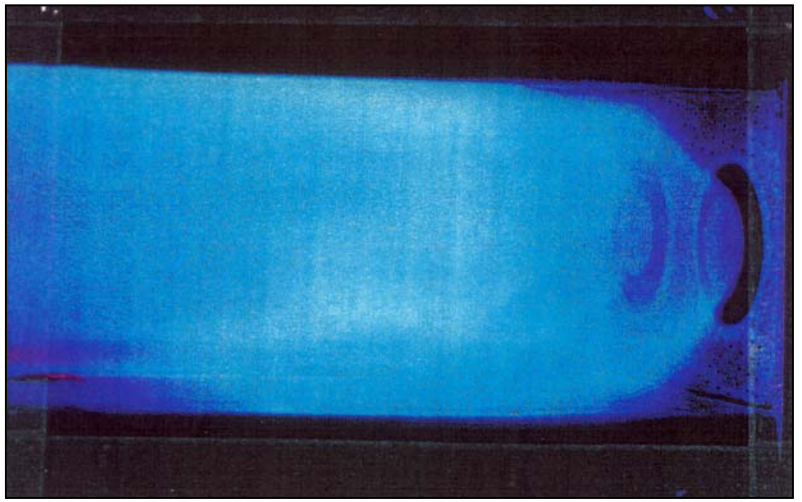


Four single-shot PLIF images of air/fuel inhomogenieties

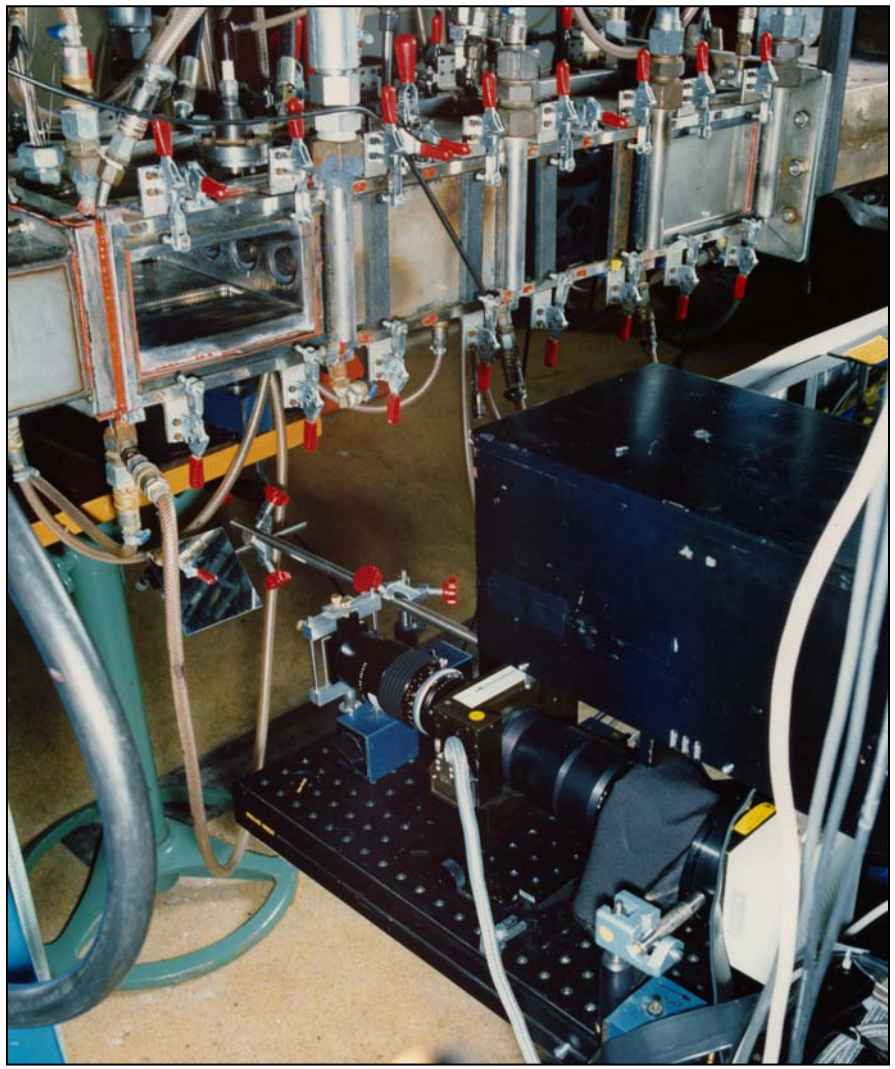
”Swirling” burners at VAC



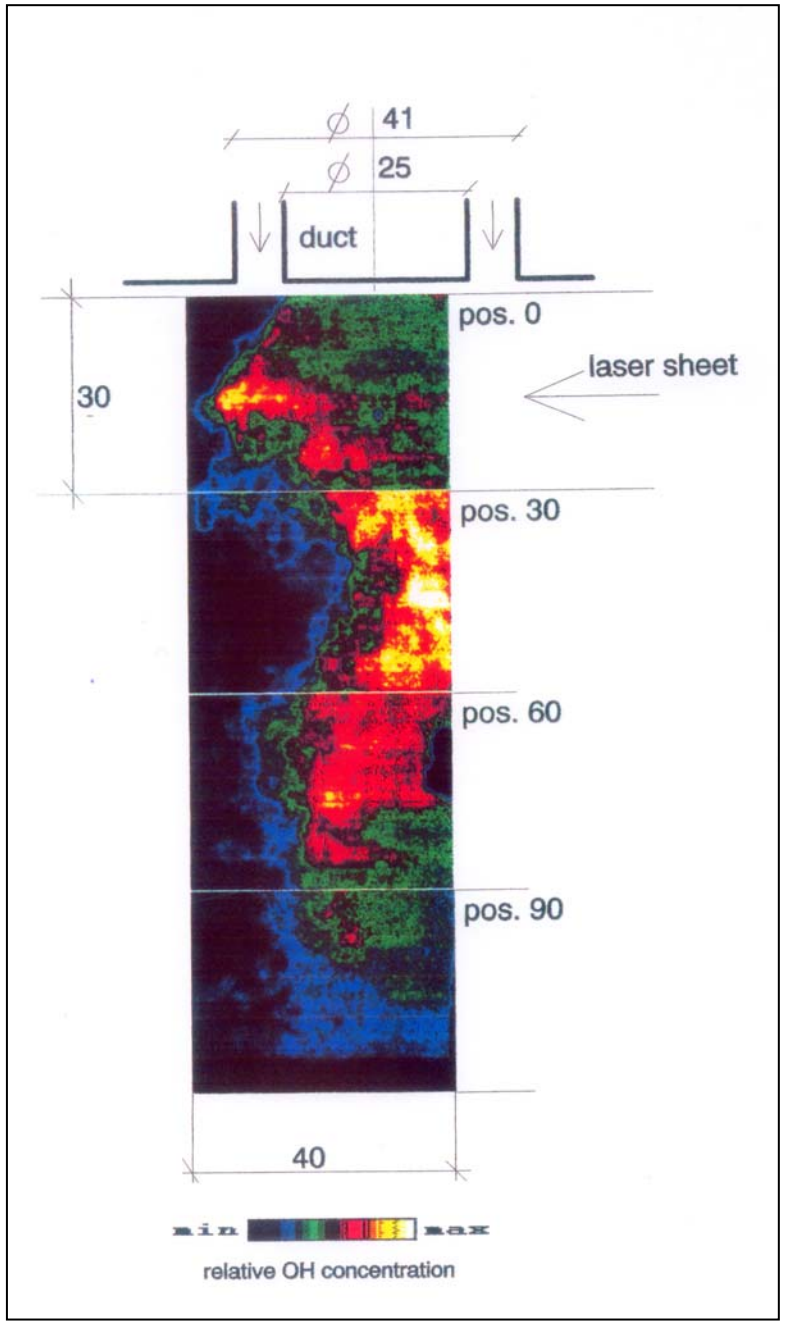




Experimental set-up

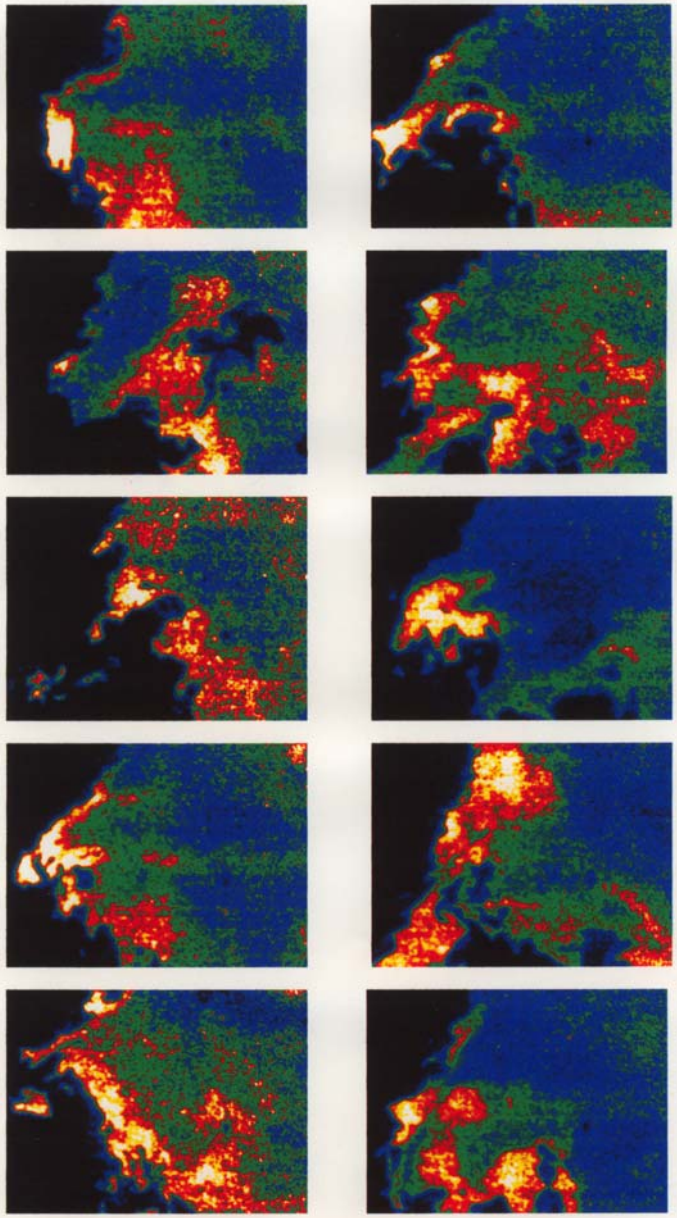


Average OH images at different spatial locations from the burners



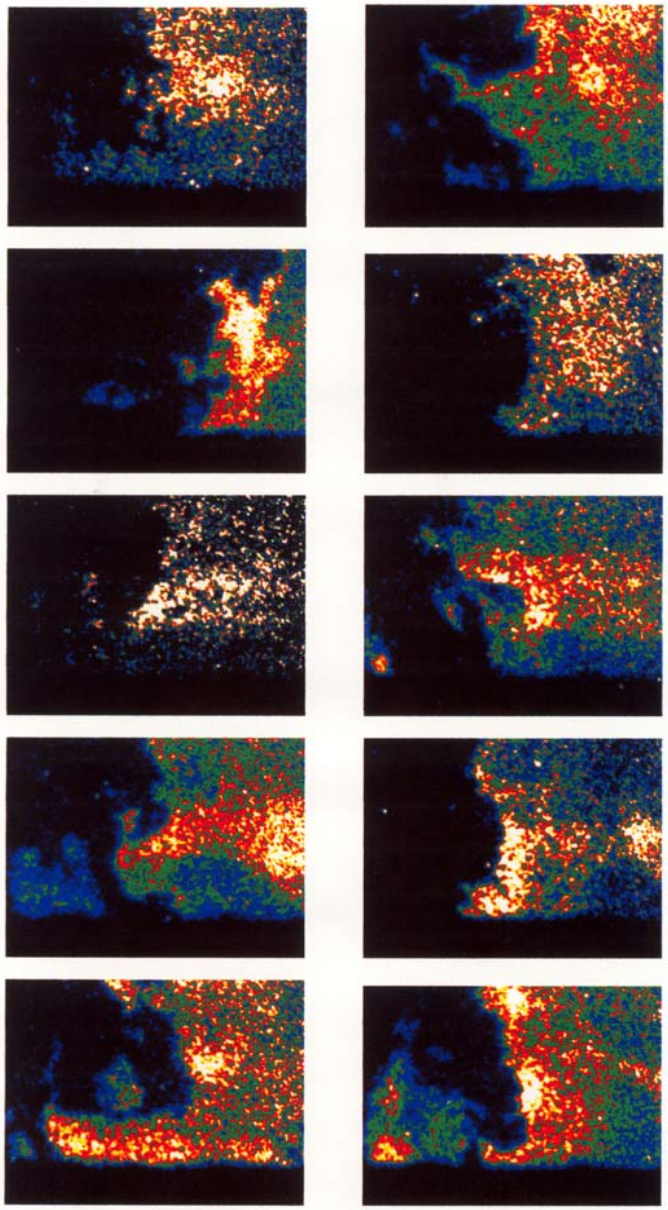
T = 565 K m = 225 g/s ϕ = 0.22 pos. 0

single shot

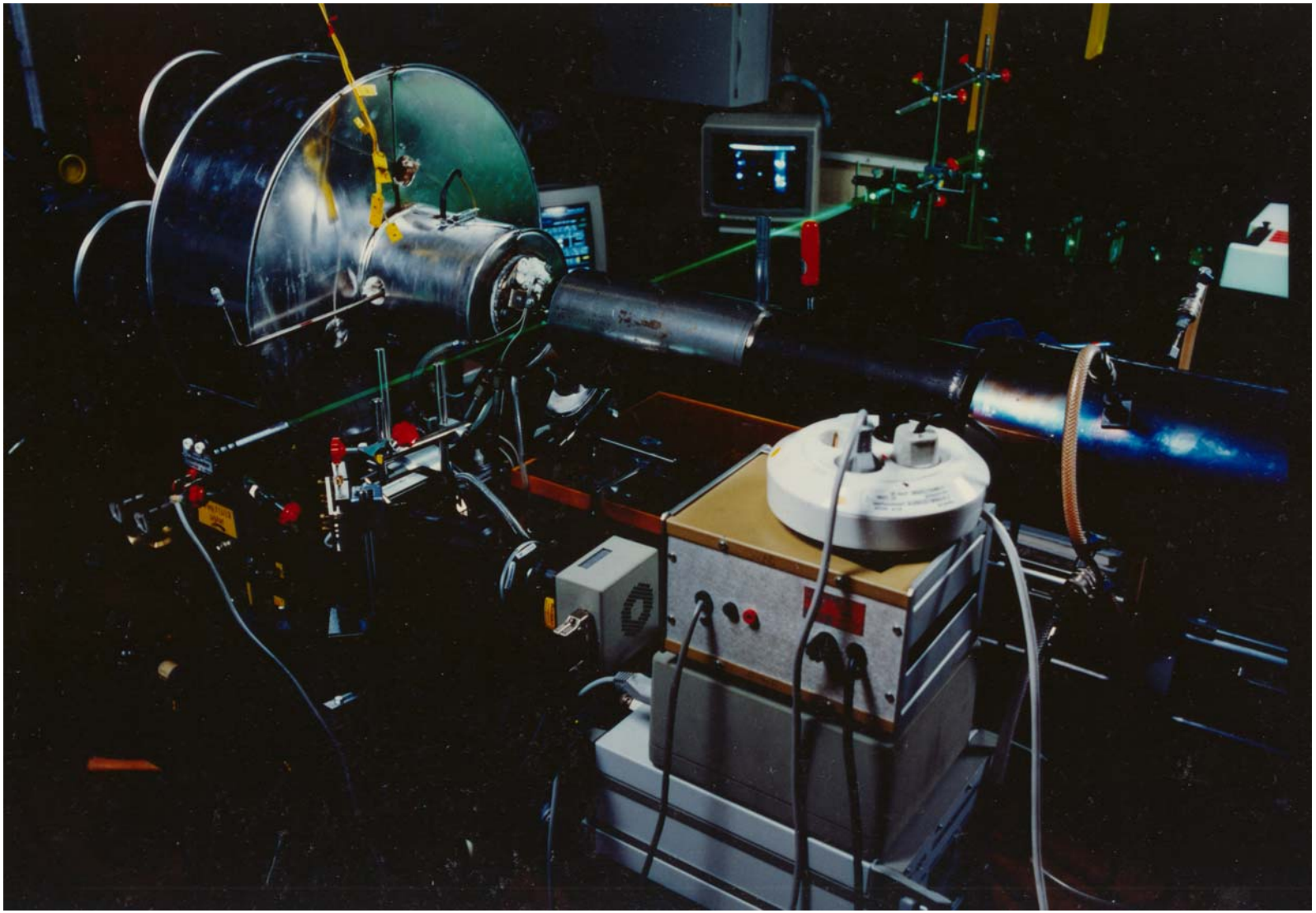


T = 288 K m = 310 g/s ϕ = 0.27 pos. 90

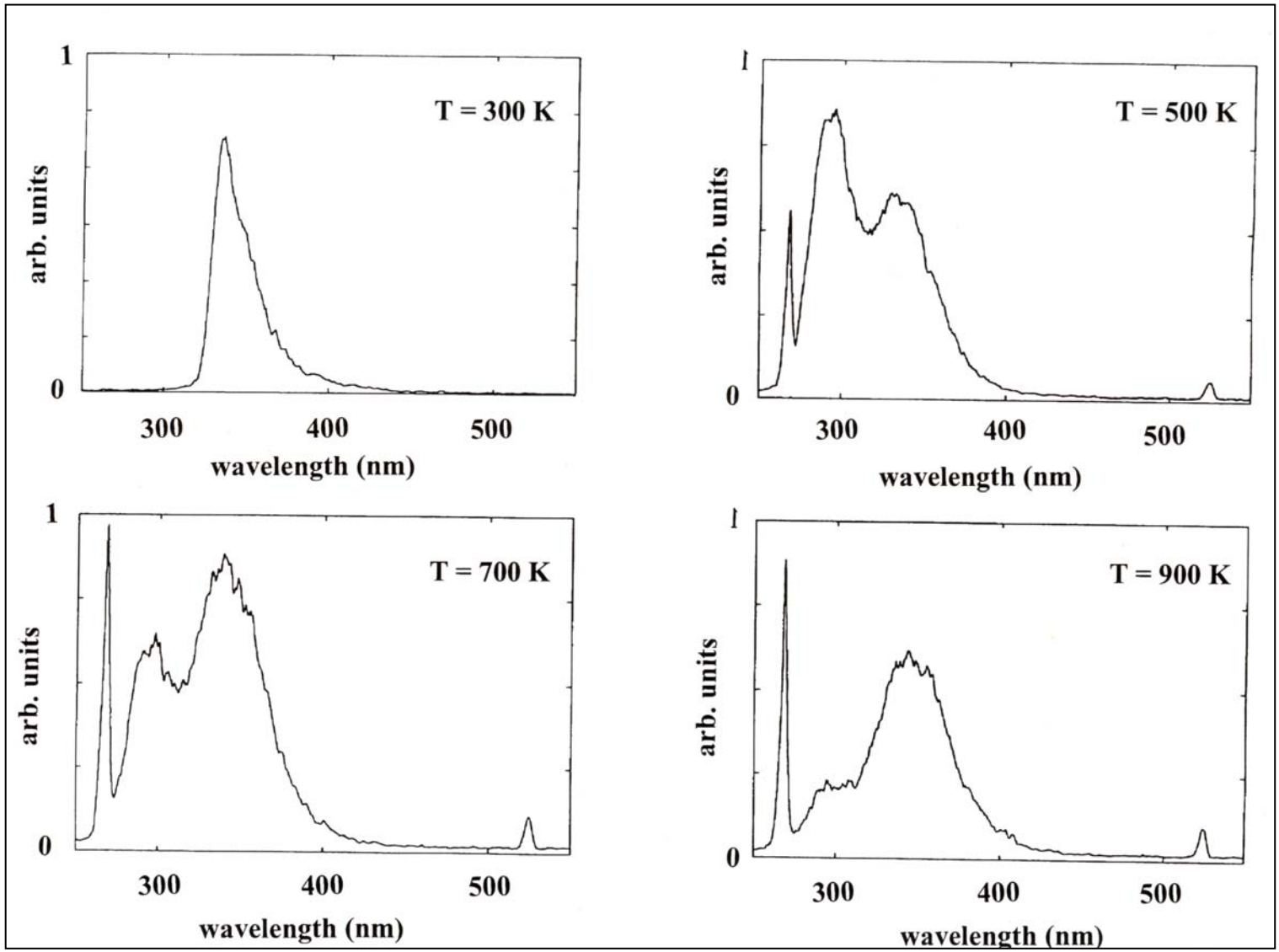
single shot



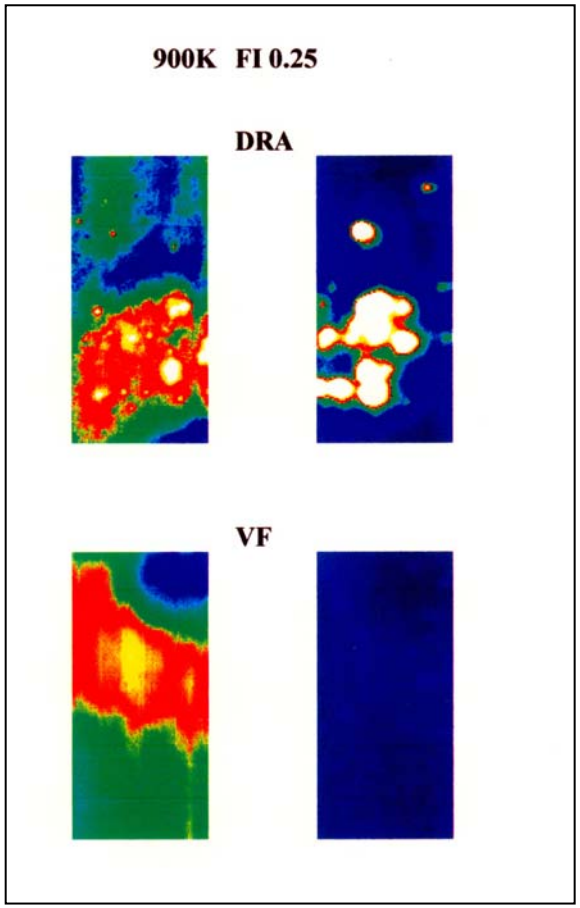
Experimental arrangements for Jet-A studies

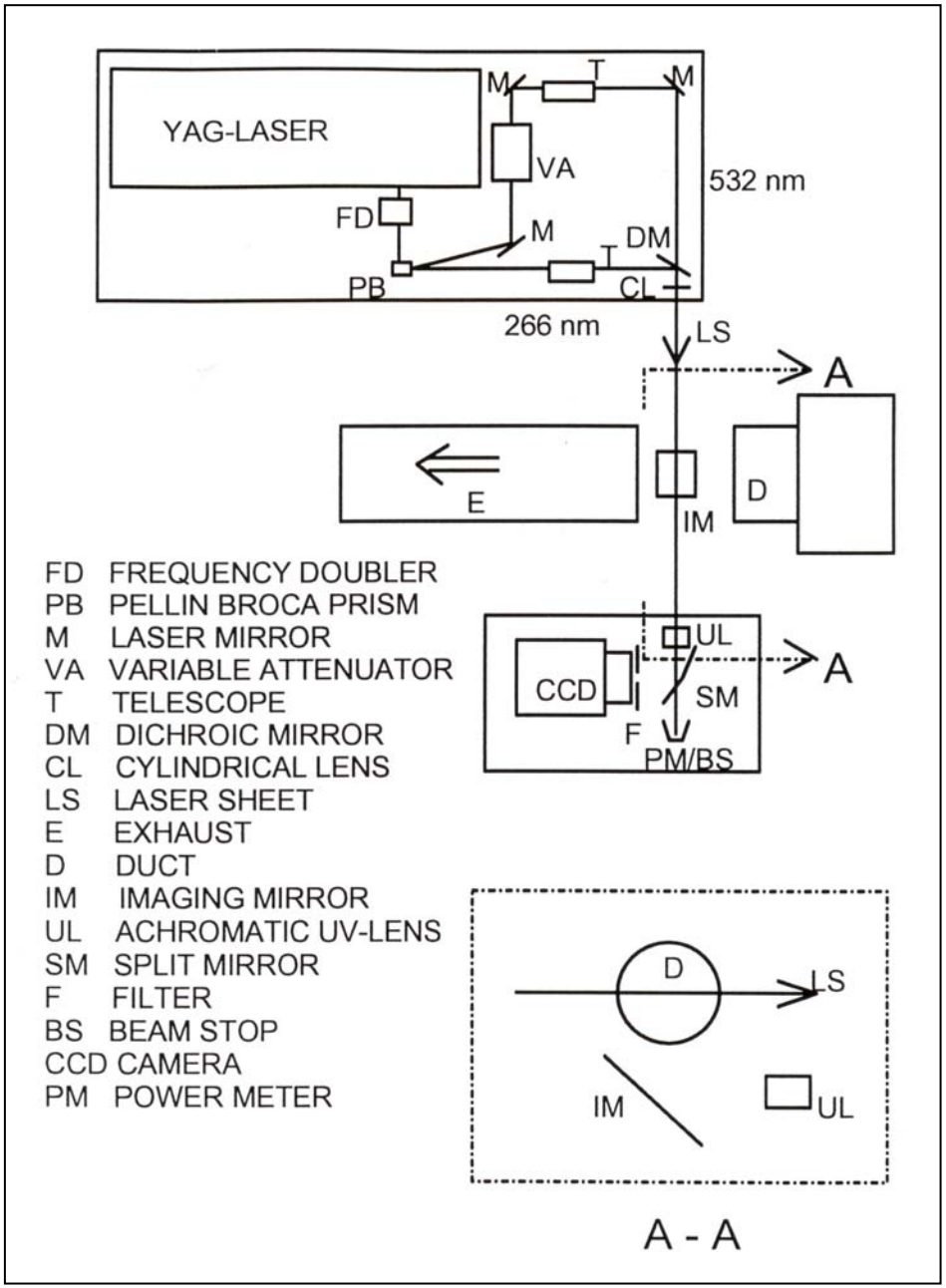


LIF spectra from JET-A at different T



Experimental set-up: simultaneous Mie scattering/LIF





LIF species visualization
c) Furnace/Biomass environments

Pyrolysis experiments I

Excitation at 266 nm

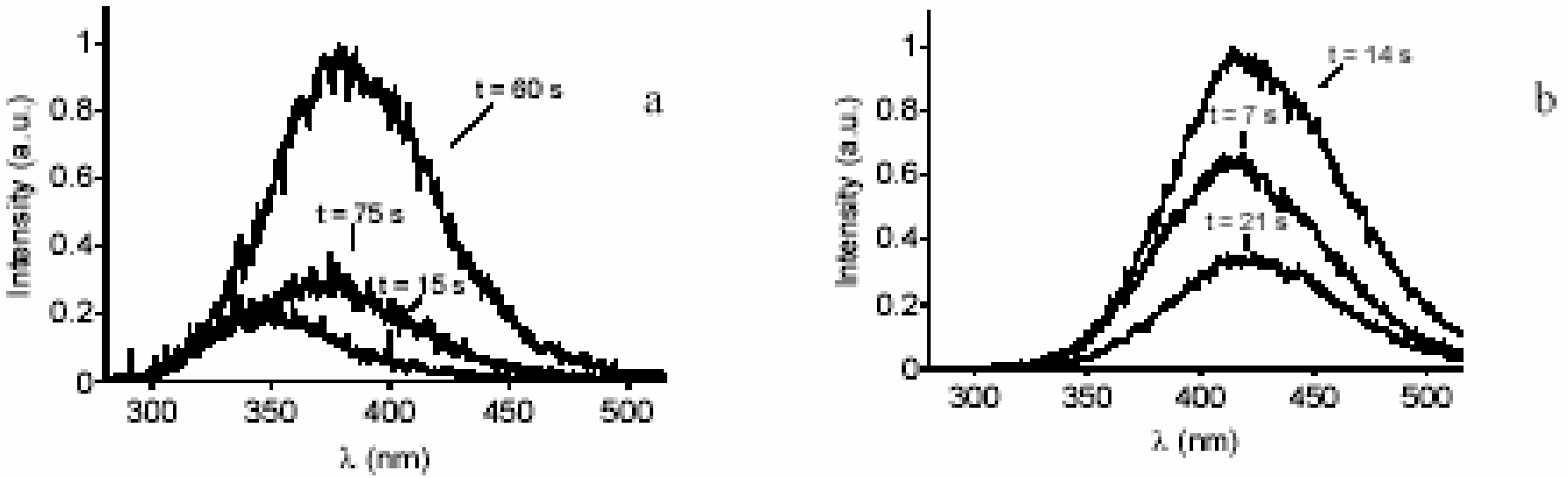
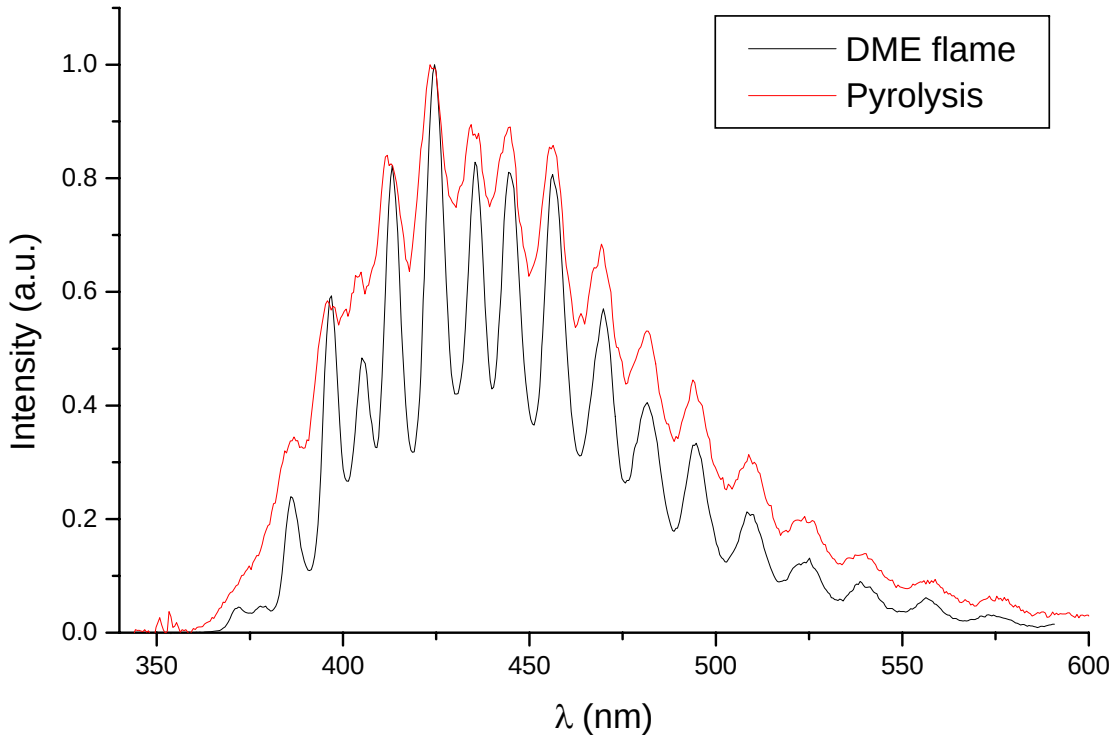


Figure 28. Laser-induced fluorescence spectra detected with excitation wavelength 266 nm at 500 °C (a) and 800 °C (b).

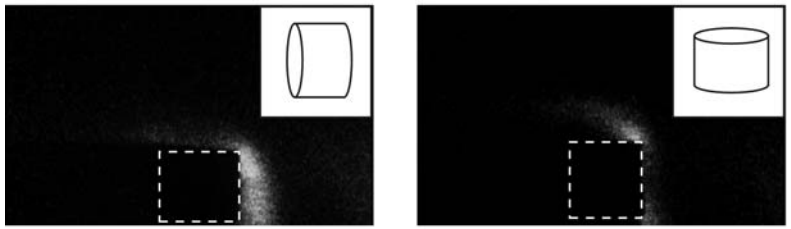
Pyrolysis experiments II

Excitation with 355 nm

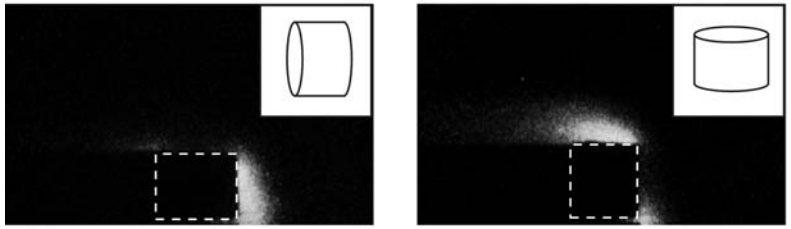


2D LIF imaging of pyrolysis products from wood particles

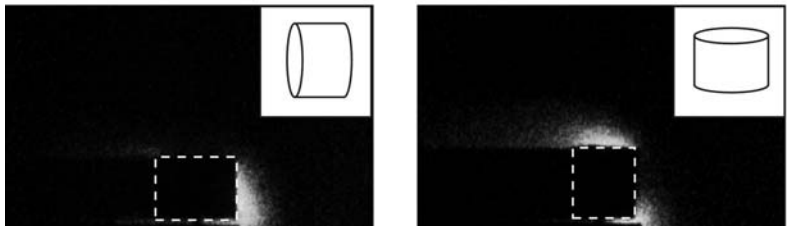
t=80 s



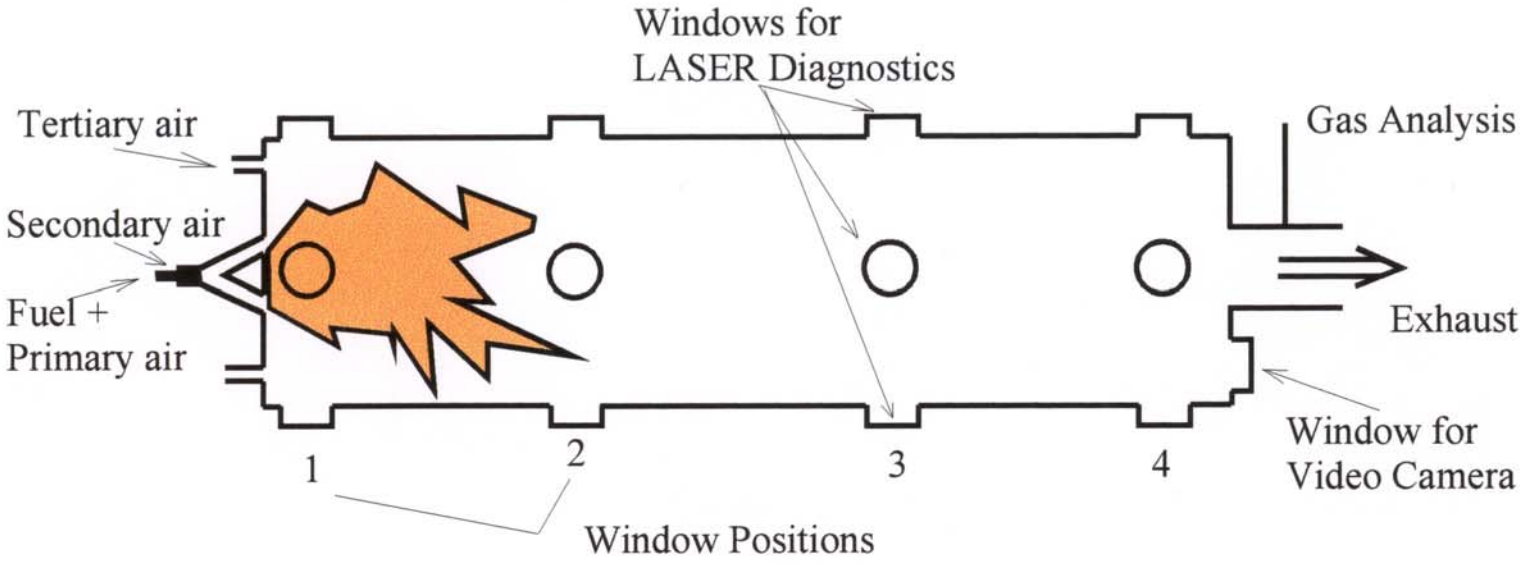
t=120 s



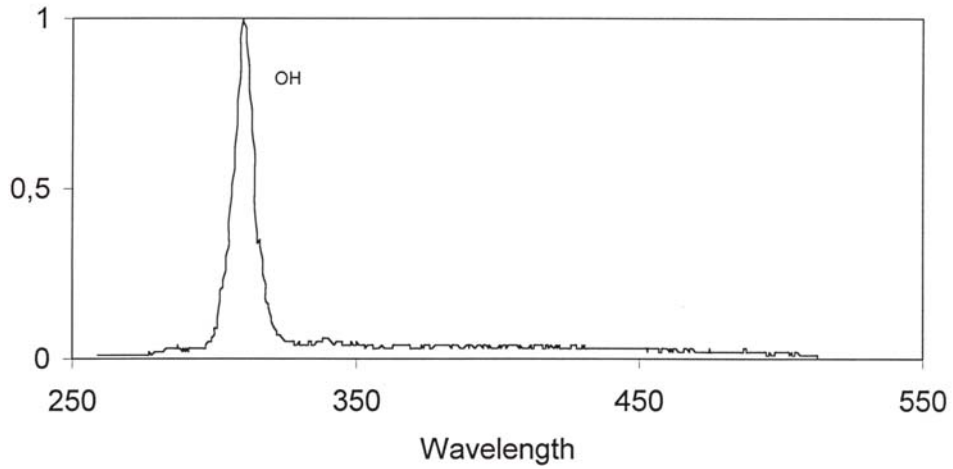
t=180 s



LIF experiments in a laboratory wood-particle fuelled burner

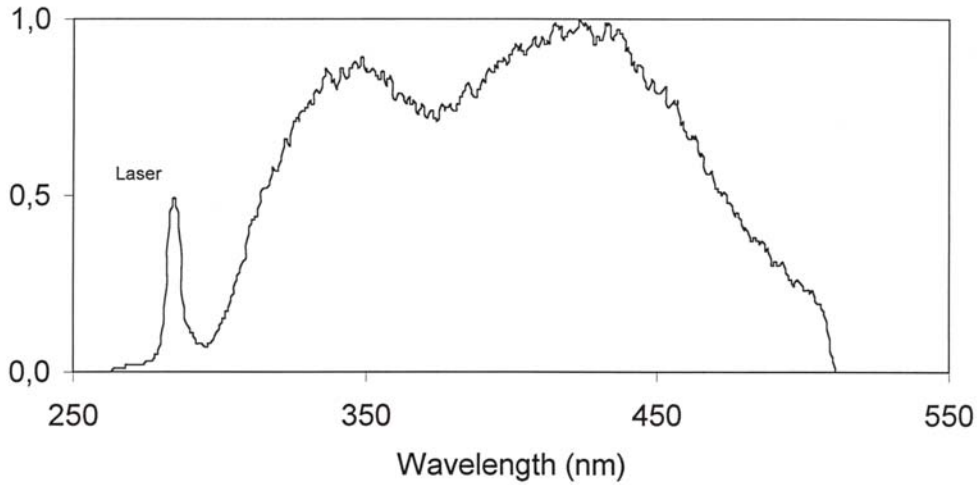


LIF spectra: exc 282 nm



Fuel: propane

Fuel: biopowder



Furnace applications - LIF