Classical measurements in thermoacoustics

or more precisely:

Non-acoustic measurements in thermoacoustics

Maria Heckl
Department of Mathematics
Keele University
Staffordshire ST5 5BG
England
m.a.heckl@keele.ac.uk

Overview

1. Chemiluminescence
2. Laser-induced fluorescence
3. Laser – Doppler anemometry
4. Particle image velocimetry
5. Summary of applications

Measurements involving acoustic pressure will be covered in the lecture by Wolfgang Polifke on "Linear time series analysis".

1. Chemiluminescence

There is no experimental method to measure directly the heat release rate from a flame → resort to optical techniques

What is chemiluminescence ?

Emission of light from radicals formed during a chemical reaction.

Combustion is a multi-step chemical reaction.
For example: methane combustion $CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$

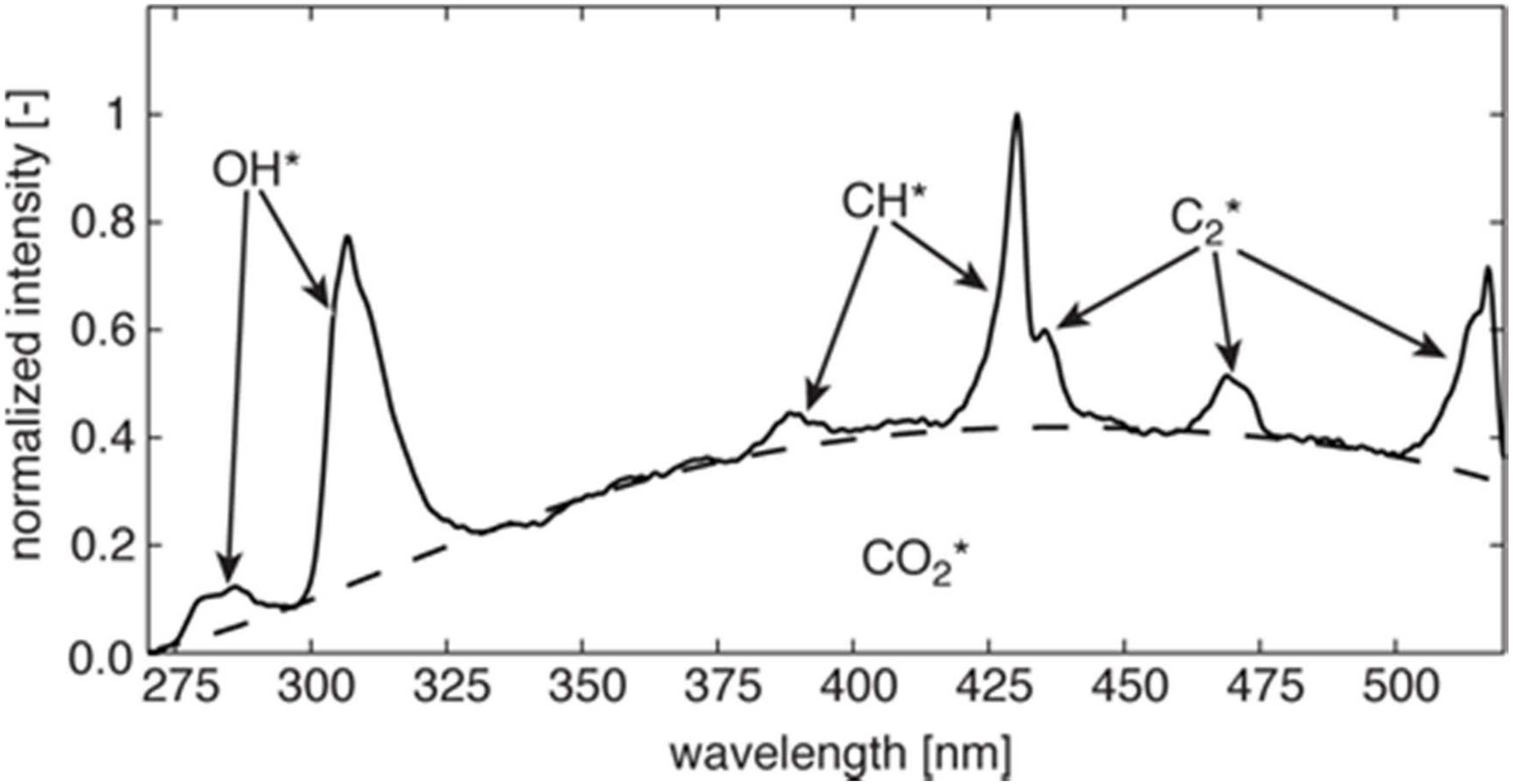
1. $CH_4 + M^* \rightarrow CH_3 + H + M$
2. $CH_4 + O_2 \rightarrow CH_3 + HO_2$
3. $CH_4 + HO_2 \rightarrow CH_3 + 2\,OH$
4. $CH_4 + OH \rightarrow CH_3 + H_2O$
5. $O_2 + H \rightarrow O + OH$
6. $CH_4 + O \rightarrow CH_3 + OH$
7. $CH_3 + O_2 \rightarrow CH_2O + OH$
8. $CH_2O + O \rightarrow CHO + OH$
9. $CH_2O + OH \rightarrow CHO + H_2O$
10. $CH_2O + H \rightarrow CHO + H_2$
11. $CHO + O \rightarrow CO + OH$
12. $CHO + OH \rightarrow CO + H_2O$
13. $CHO + H \rightarrow CO + H_2$
14. $H_2 + O \rightarrow H + OH$
15. $H_2 + OH \rightarrow H + H_2O$
16. $CO + OH \rightarrow CO_2 + H$
17. $H + OH + M \rightarrow H_2O + M^*$
18. $H + H + M \rightarrow H_2 + M^*$
19. $H + O_2 + M \rightarrow HO_2 + M^*$

from: http://en.wikipedia.org/wiki/Methane

The species M* signifies an energetic third body, from which energy is transferred during a molecular collision.

Some interim steps produce short-lived radicals, e.g. OH^*, CH^*, C_2^*, CO_2^*

The decay of a radical to a lower energy level causes light emission:



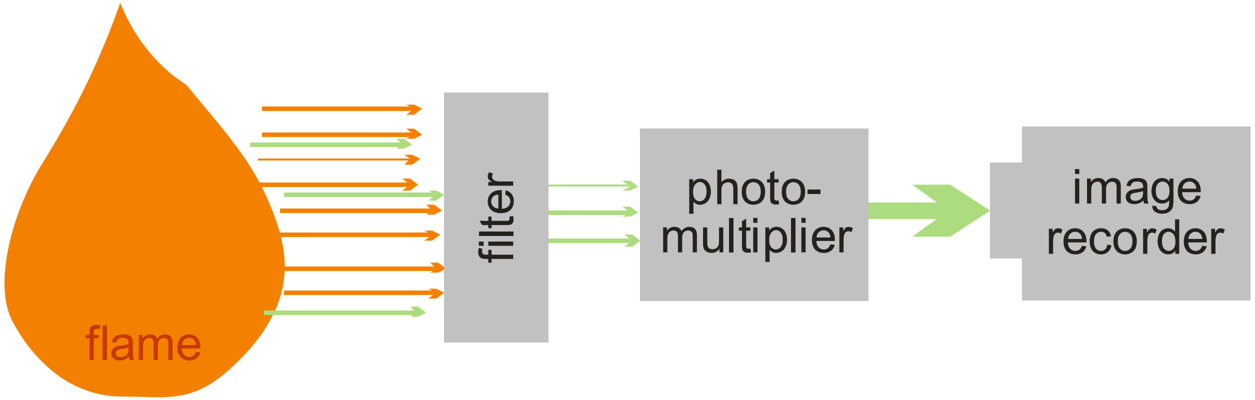
typical chemiluminescence spectrum of a premixed hydrocarbon flame
from Sattelmayer website

CO_2^*: 300 – 600 nm, broad-band

OH^* : 308 nm
CH^*: 431 nm
C_2^*: 513 nm
narrow-band

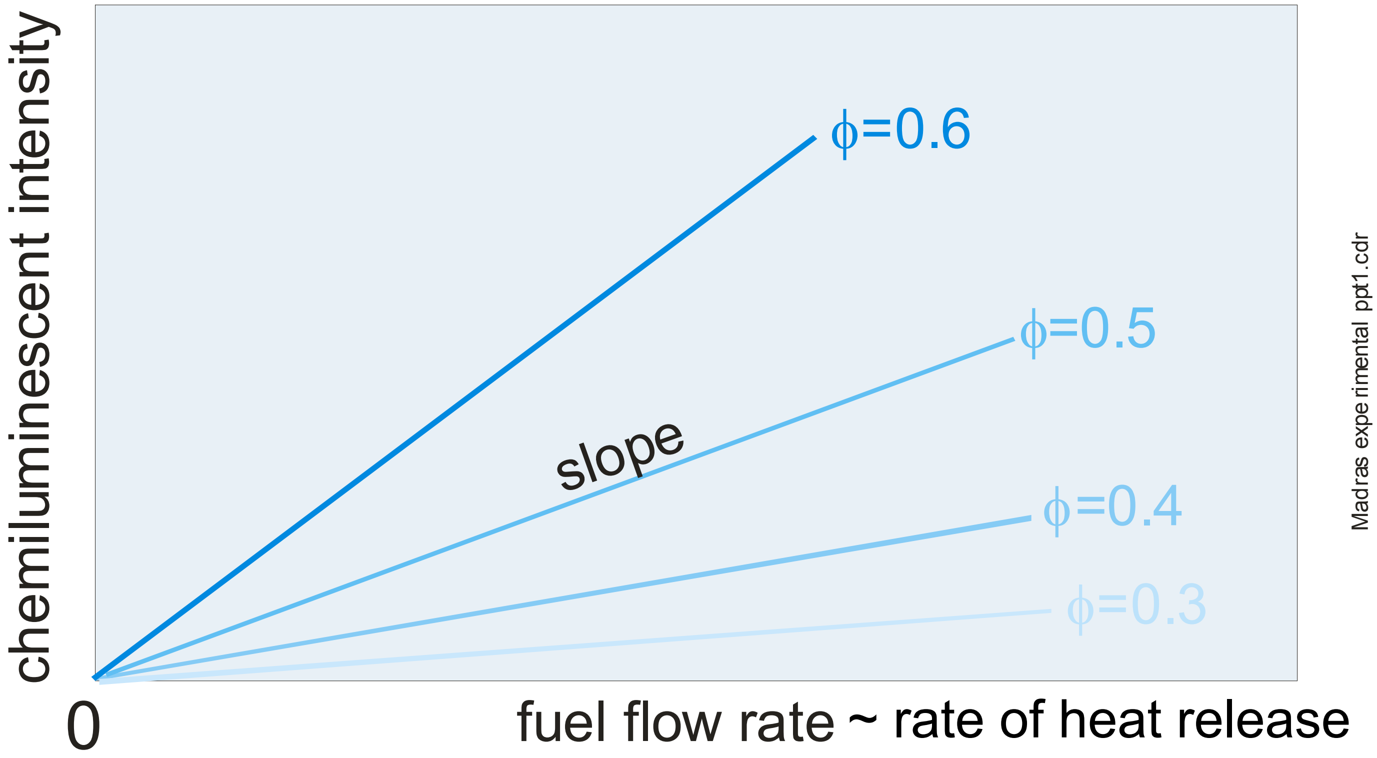
The intensity of the light emitted from the radicals is an indictor for the rate of heat release in lean, premixed hydrocarbon flames.

Typical experimental setup for chemiluminescence measurements



Madras experimental ppt4.cdr

Chemiluminescence emission vs fuel flow rate for different equivalence ratios:

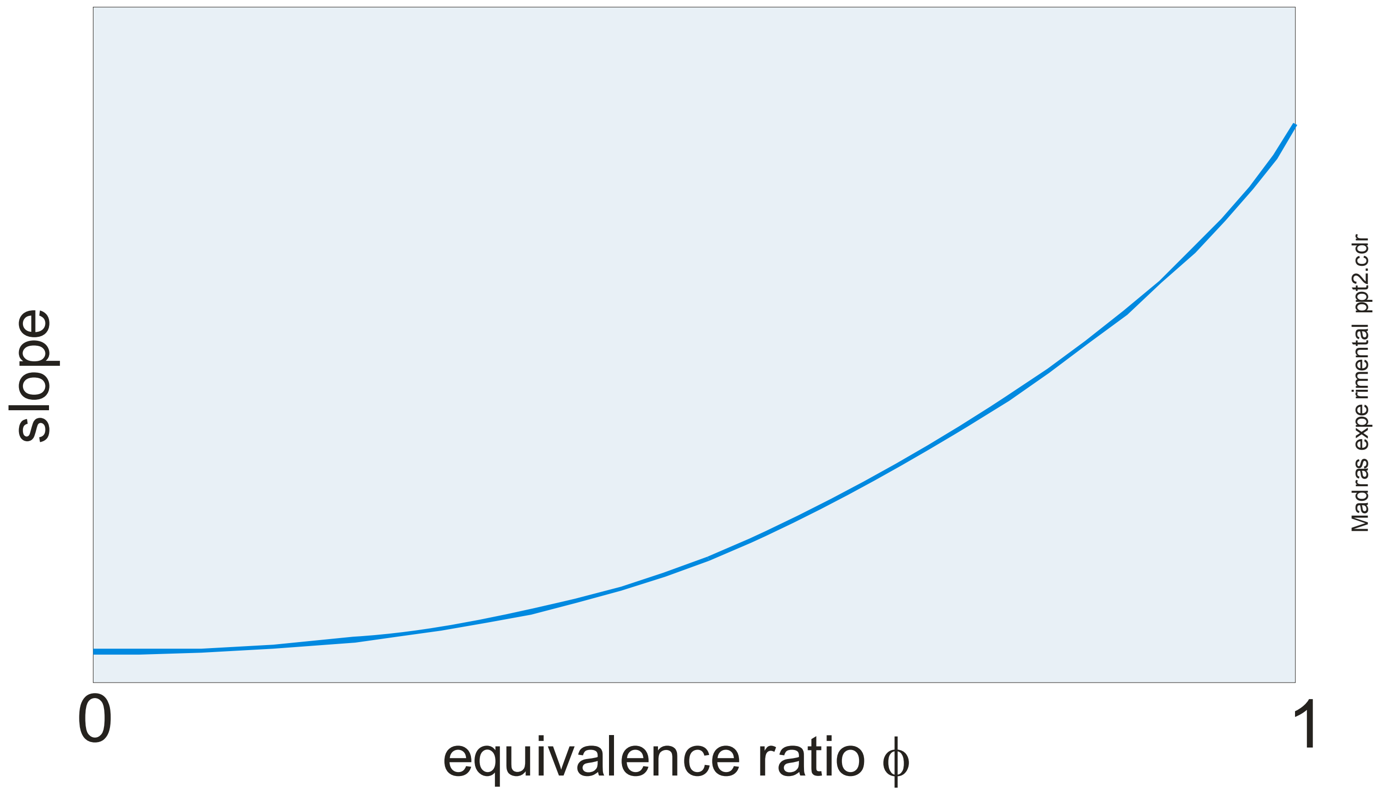


Madras experimental ppt1.cdr

linear dependence

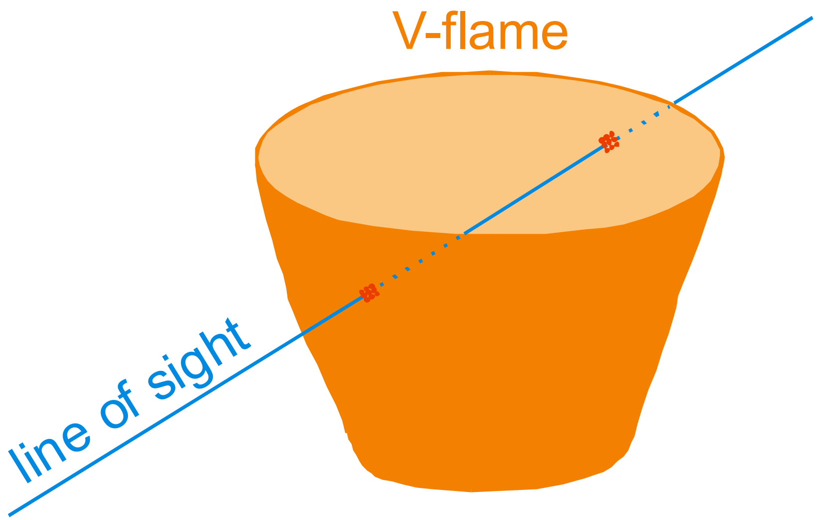
slope increases exponentially with Φ

Slope (ratio of chemiluminescence intensity to fuel flow rate) vs equivalence ratio Φ



The exponential increase is due to the exponential dependence of the reaction rate on temperature.

What can we measure?



Madras experimental ppt3.cdr

Local measurement:

intensity I_{2D} , integrated along line of sight

For axisymmetric flames, the *local* intensity I_{local} can be reconstructed with special software (e.g. “onion peeling”).

local heat release rate: $q(\mathbf{x}) = C\, I_{local}(\mathbf{x})$

constant, depends on Φ, temperature, etc.

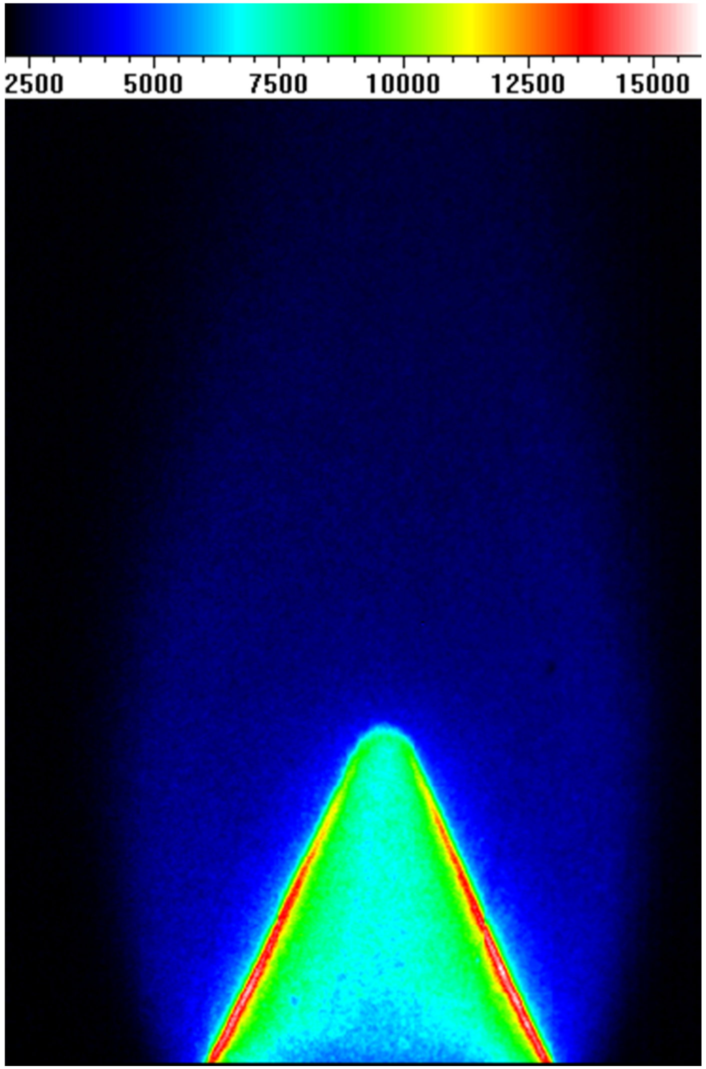
Global measurement:

intensity I_{global} , integrated over flame volume

This gives the global heat release rate *Q:* $Q = C\, I_{\mathrm{global}}$

C is determined by calibration in the steady state.

Example: OH* chemiluminescence in a Bunsen flame



from: http://www.ieni.mi.cnr.it/research_themes/reactive-systems-and-advanced-diagnostics/optical-diagnostic-techniques-in-combustion

Dynamic measurements

The same technique is applied for time-dependent rate of heat release:

$$Q(t) = C\,\mathcal{I}_{\mathrm{global}}(t)\;,\quad q(\mathbf{x},t) = C\,\mathcal{I}_{local}(\mathbf{x},t)$$

The Rayleigh criterion

$$\overline{p'(t)q(t)} = \frac{1}{T}\int_0^T p'(t)q(t)\,\mathrm{d}t \quad \begin{array}{ll} > 0 & \text{instability} \\ < 0 & \text{stability} \end{array}$$

is the basis for analysis of thermoacoustic instability.

The *Rayleigh index* distribution can be determined from local dynamic measurements:

$$R(\mathbf{x},t) = \frac{1}{T}\int_0^T p'(\mathbf{x},t)q(\mathbf{x},t)\,\mathrm{d}t$$

T : period of oscillation (integration over one cycle)

$q(\mathbf{x},t)$: local rate of heat release at position **x**

$p'(\mathbf{x},t)$: acoustic pressure at position **x**

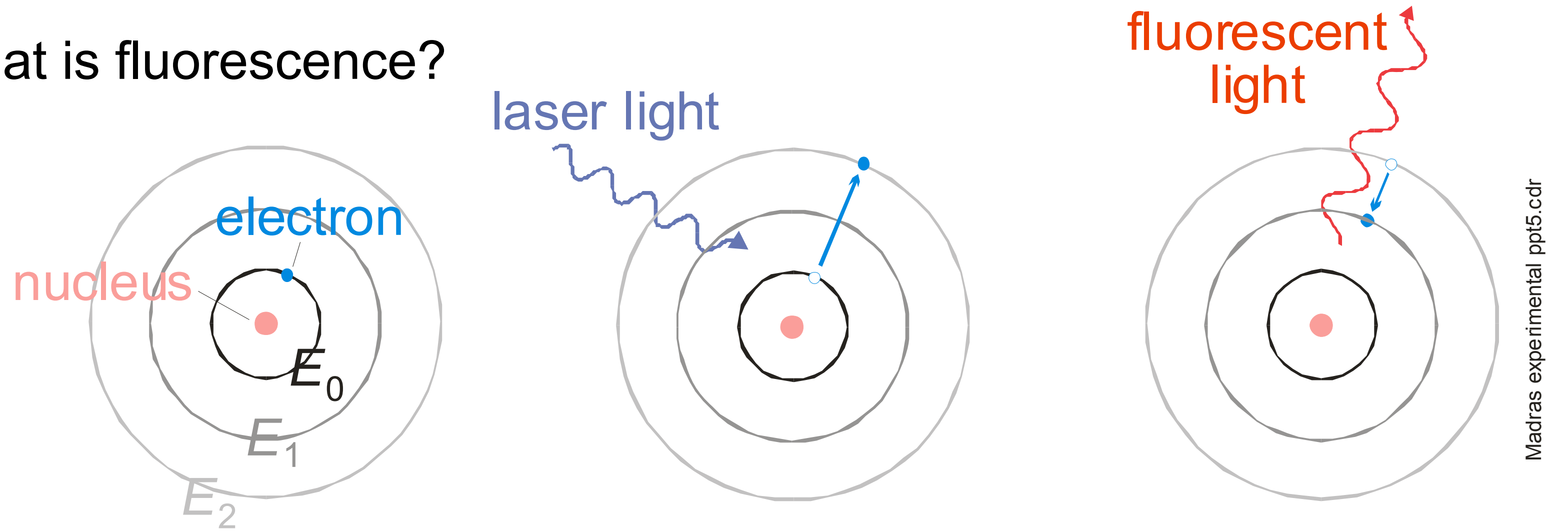
Potential problems

1. Φ is non-uniform in partially premixed flames → *C* is *not* constant

2. In syngas flames, there is no clear relationship between concentration of OH or CH radicals and the heat release rate.

2. Laser-induced fluorescence (LIF)

What is fluorescence?



basic state excited state fluorescing state

incident light from laser, tuned to a particular transition, e.g. $E_0 \rightarrow E_2$

emitted light results from reverse transition, e.g. $E_2 \rightarrow E_1$

wavelength: $\lambda_{\text{emitted}} > \lambda_{\text{incident}}$

emitted light intensity: $I_{\text{emitted}} = C\, n_i$

constant, depends on temp, pressure, etc.

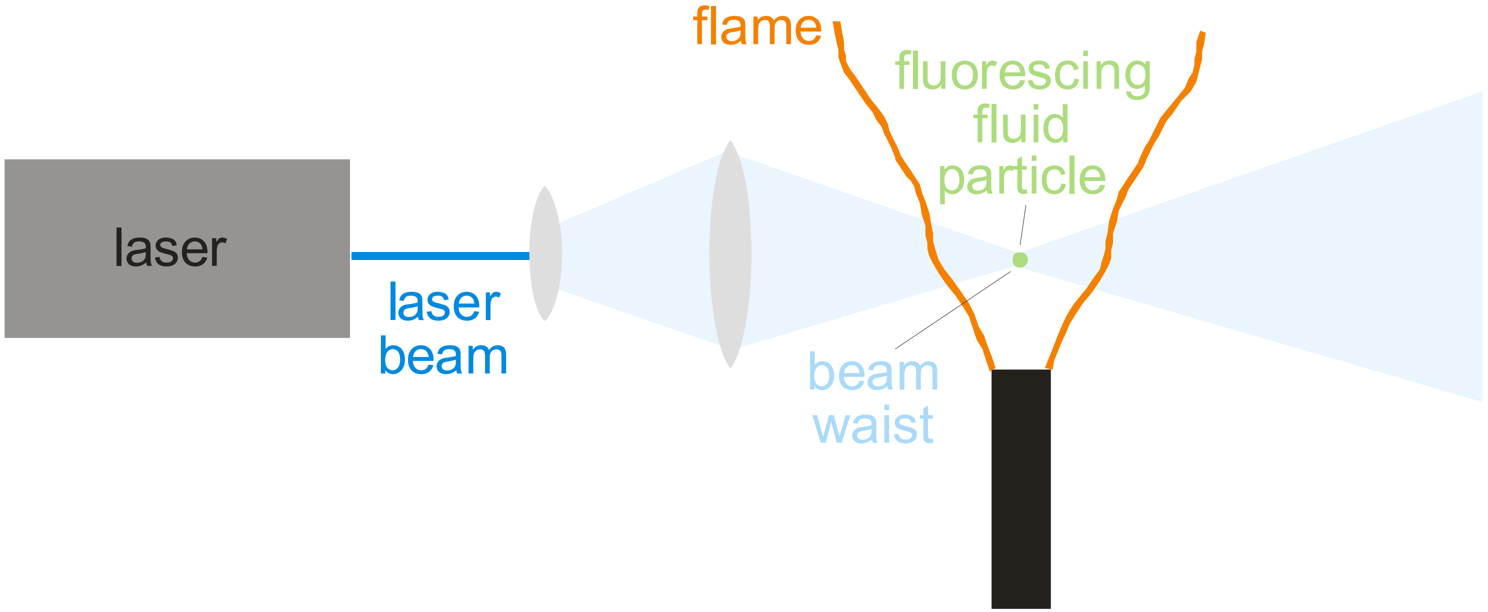
density of species *i*

The constant *C* is determined by calibration.

→ The concentration of a species can be measured.

Application: quantitative measurements of equivalence ratio distribution

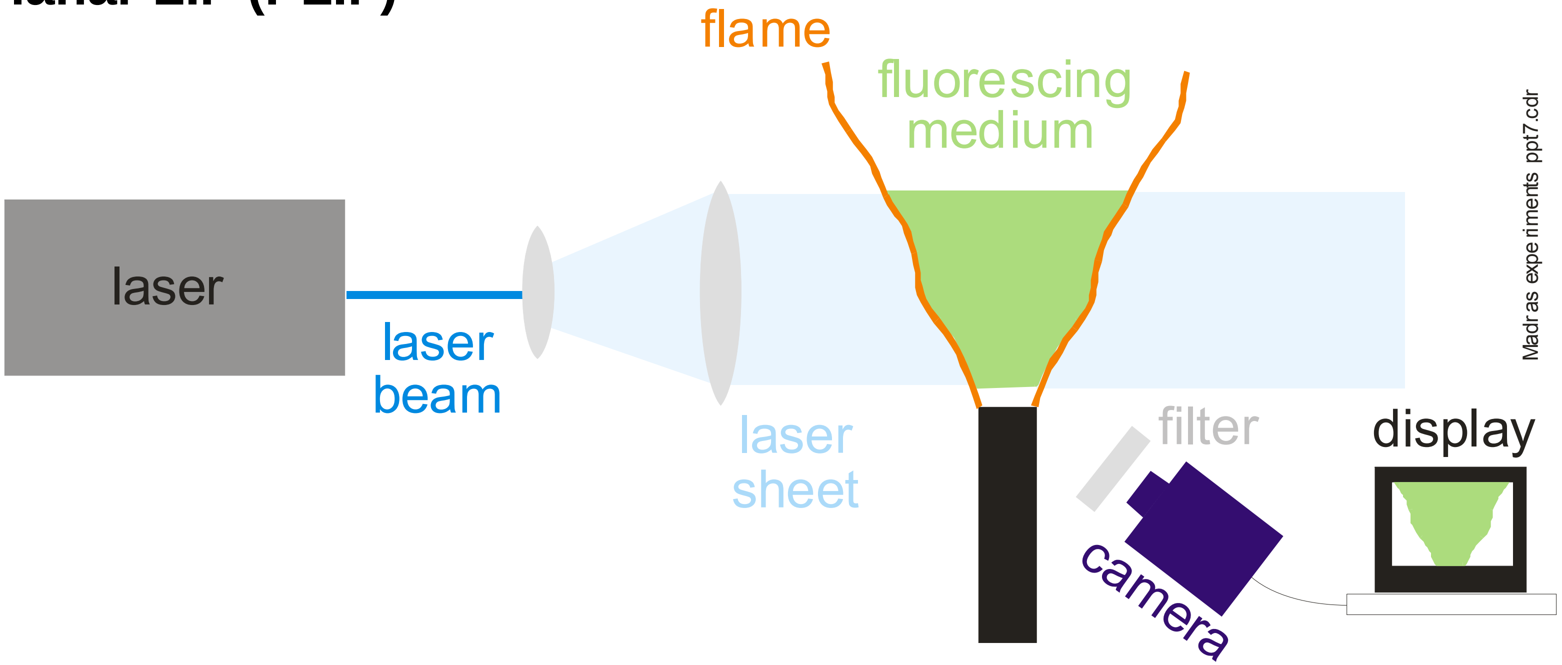
Point measurement (1-D LIF)



Madras experiments ppt6.cdr

spatial resolution: sub-millimetre

Planar LIF (PLIF)



PLIF works best in gas-fuelled combustors.

LIF-active species: CH, OH, NO, N_2, CH_4, etc.   otherwise seed

Pulsed laser → single-shot images (kHz rate)

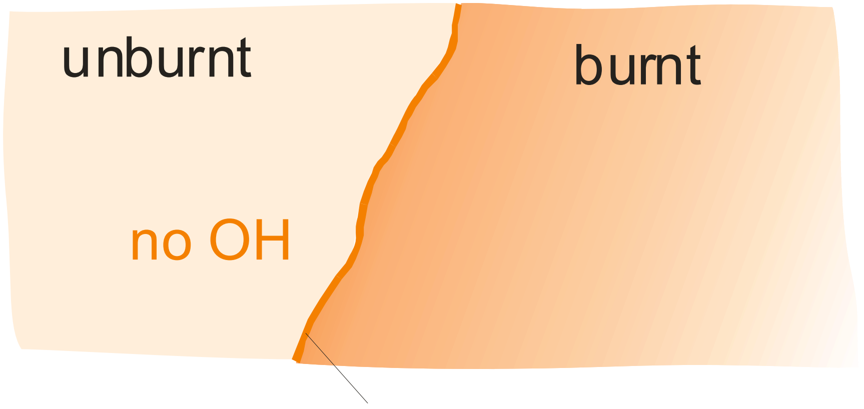
advantages: detects chemical species at ppm level

no issue with line-of-sight integration

OH - PLIF

Application: flame structure measurement

OH* is produced during combustion and lives relatively long



Madras experiments ppt9.cdr

steep gradient in OH concentration

light intensity from OH* radical: $I_{OH} = C\, n_{OH}$

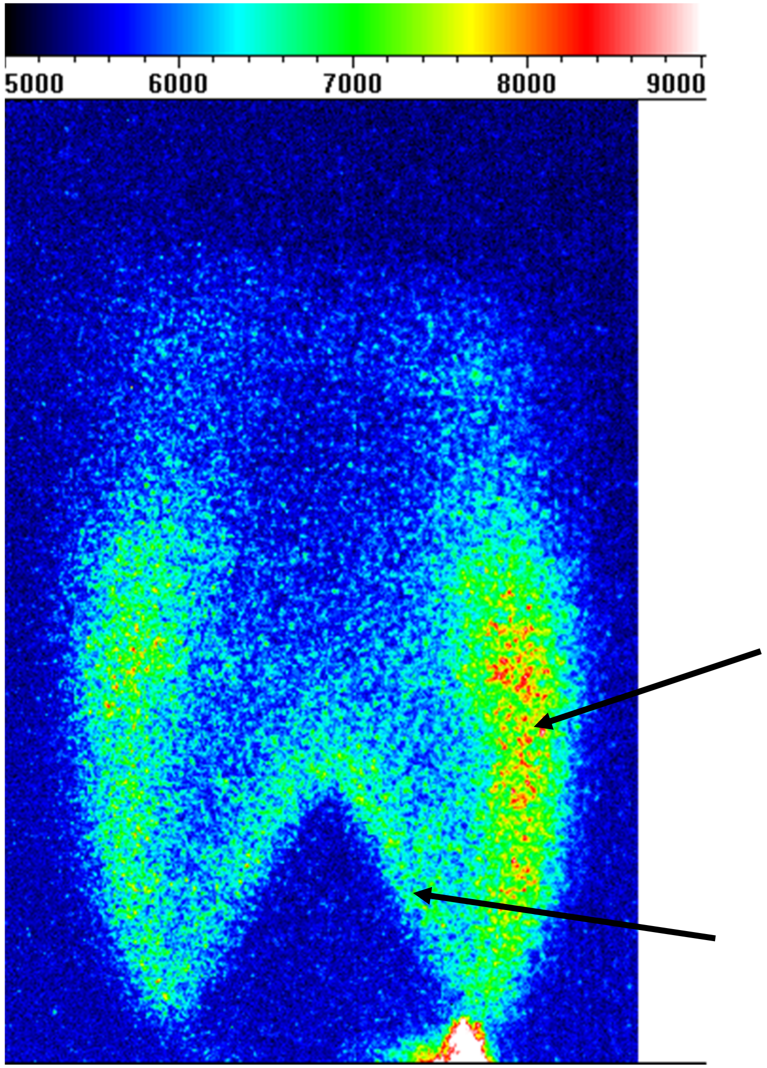
advantages: images show flame surface clearly

strong OH-PLIF signals (good signal/noise ratio)

single-shot measurement → map of flame

pulsed laser → “video” of flame movement (kHz rate)

Example: OH – PLIF image of a Bunsen flame

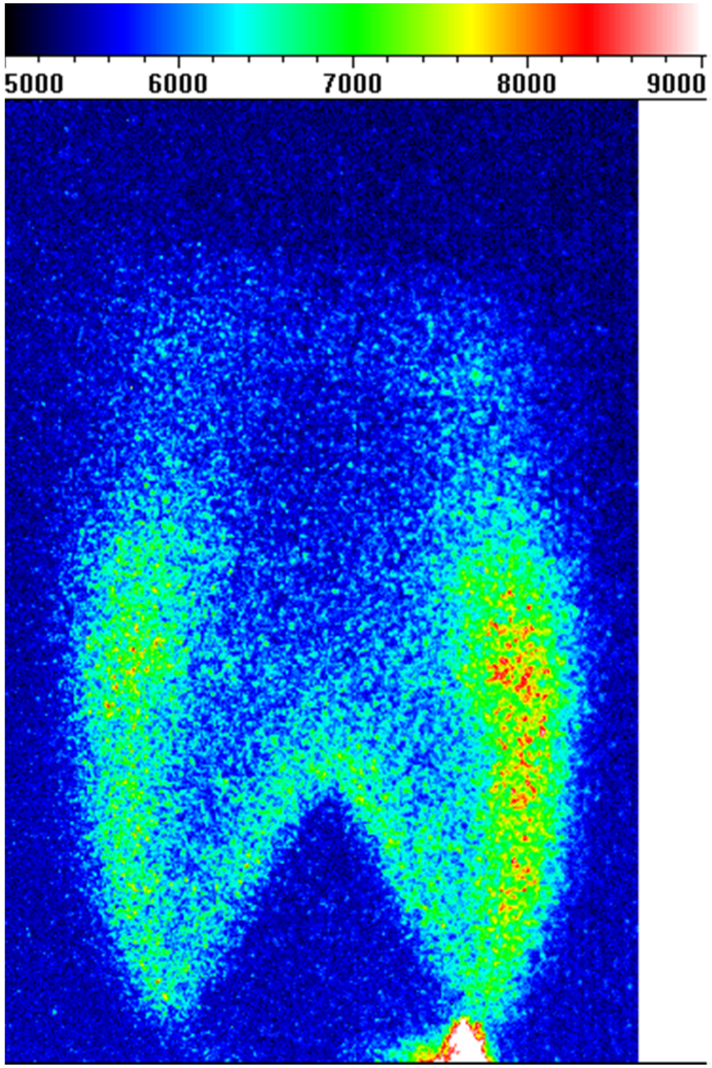


secondary reaction zone with surrounding air

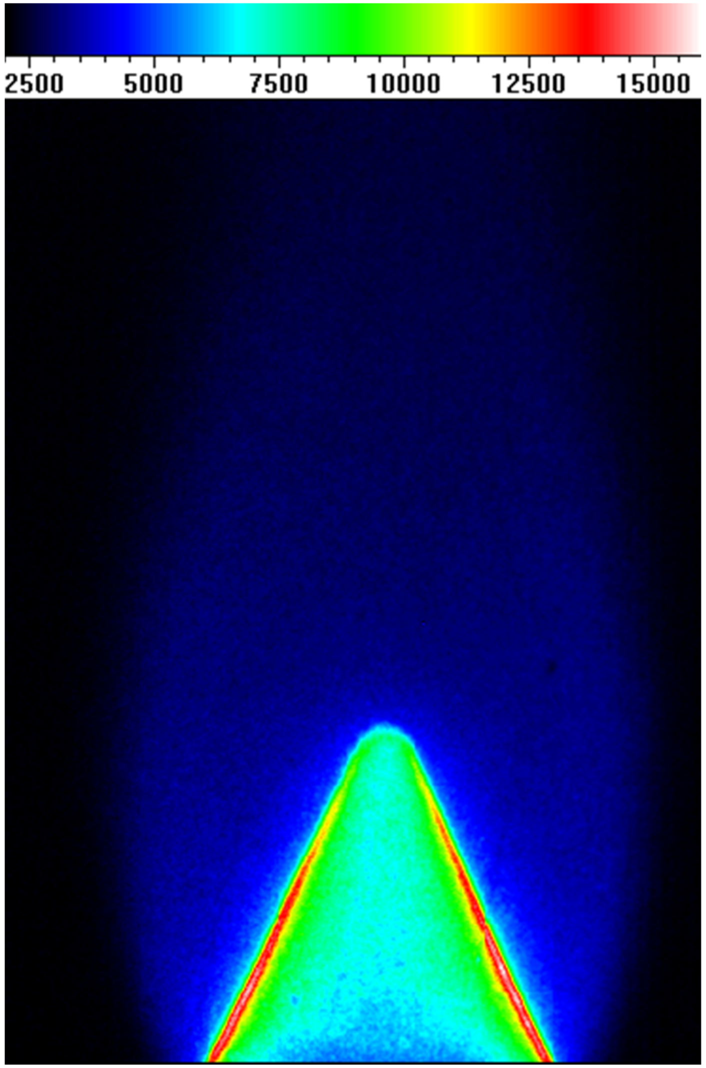
primary reaction zone

from http://www.ieni.mi.cnr.it/research_themes/reactive-systems-and-advanced-diagnostics/optical-diagnostic-techniques-in-combustion

comparison of Bunsen flame images



OH - PLIF



line-of-sight OH* chemiluminescence

HCO fluorescence

Application: measurement of heat release rate

HCO radical is produced during combustion

light intensity from HCO radical: $I_{\mathrm{HCO}} = C\, q$

alternative to chemiluminescence

advantages:

HCO concentration is accurate indicator of local heat release rate.
spatially resolved heat release rate measurements

disadvantages:

HCO fluorescence signals are typically weak (poor signal/noise ratio)

Flow – tracer PLIF

Application: visualisation of fuel distribution
(changes due to mixing or burning)

Fuel is seeded with tracer.

light intensity emitted from tracer particles:

mixture fraction of tracer

$$I_{\text{tracer}} = C\, n_{\text{tracer}}$$

$$n_{\text{tracer}} \propto n_{\text{i}}$$

mixture fraction of targeted species

popular tracer: acetone (similar to common hydrocarbon fuels)

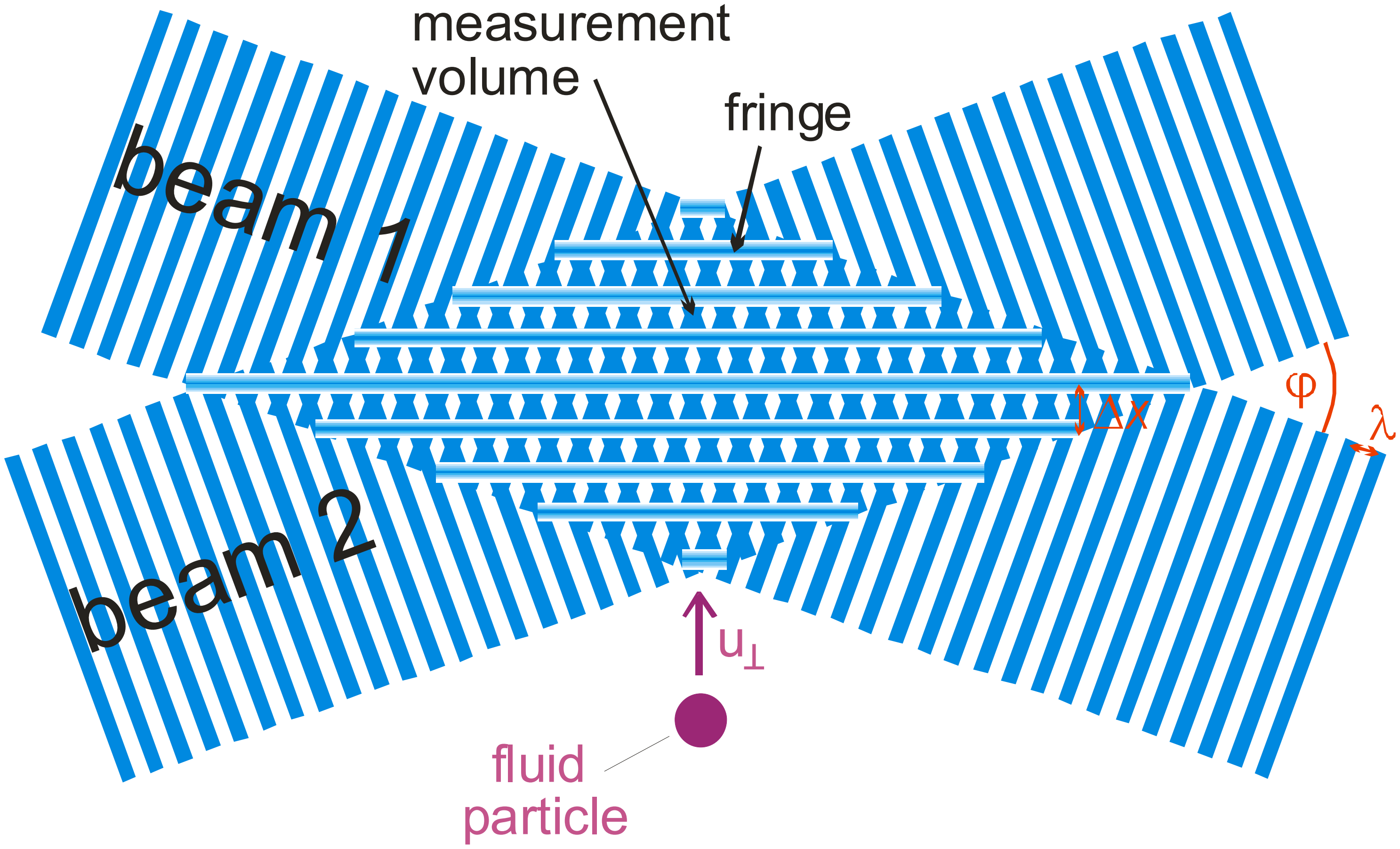
advantage: particular species can be targeted.

3. Laser – Doppler anemometry

application: measurement of time-dependent flow velocities

Basic principle

superimpose two laser beams with the same wavelength and amplitude



Madras experiments ppt8.cdr

Interference pattern: fringes with spacing $\Delta x = \dfrac{\lambda}{\sin(\varphi/2)}$

Fluid particle travels through measurement volume.

→ periodic illumination with frequency *f* (flicker frequency)

Light is collected by receiving optics and photodetector.

The particle velocity can be determined: $u_\perp = f\ \Delta x$

This is the velocity component normal to the fringes.

To measure all 3 components of the particle's velocity vector, use 3 lasers, each with a different wavelength.

Ambiguity: $u_\perp$ and $-u_\perp$ cannot be distinguished.

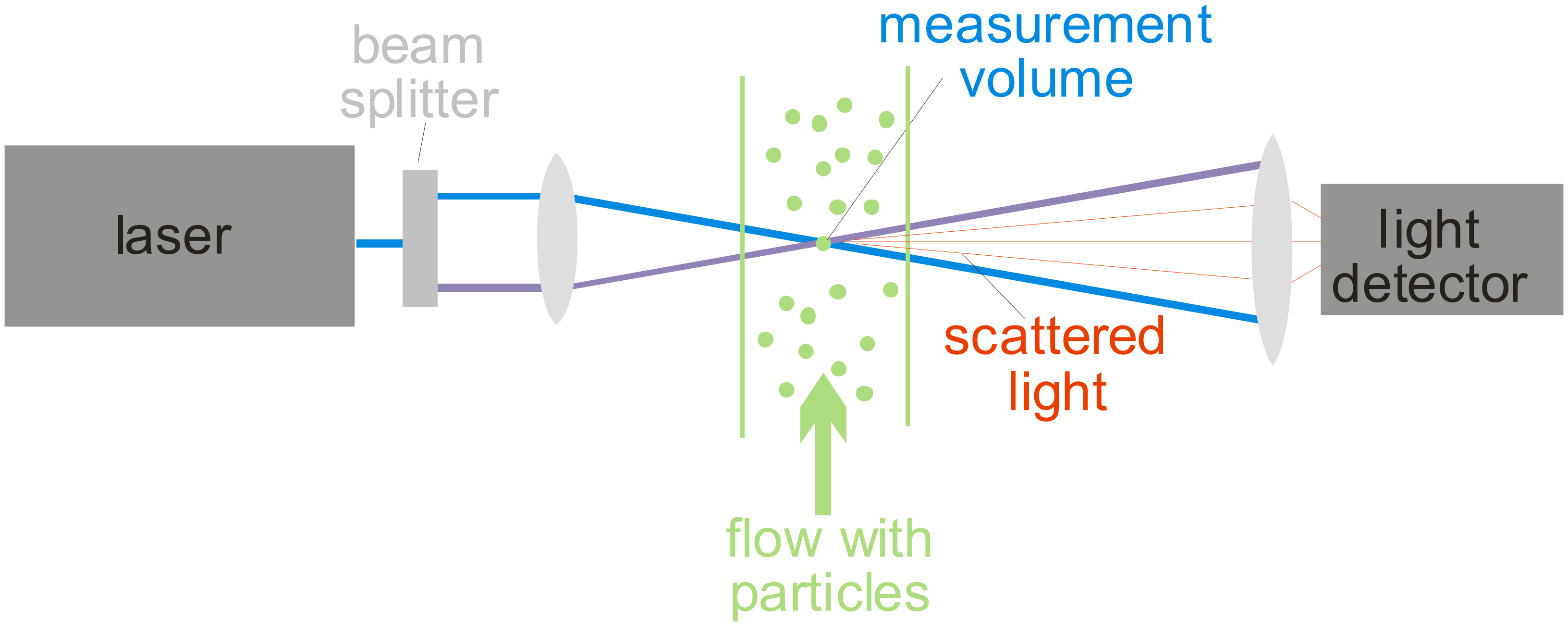
Solution: Instead of a stationary fringe pattern, use one that travels.

This is done by shifting the wavelength of one of the beams.

fringes and particle move in same direction: low flicker frequency

fringes and particle move in opposite direction: high flicker frequency

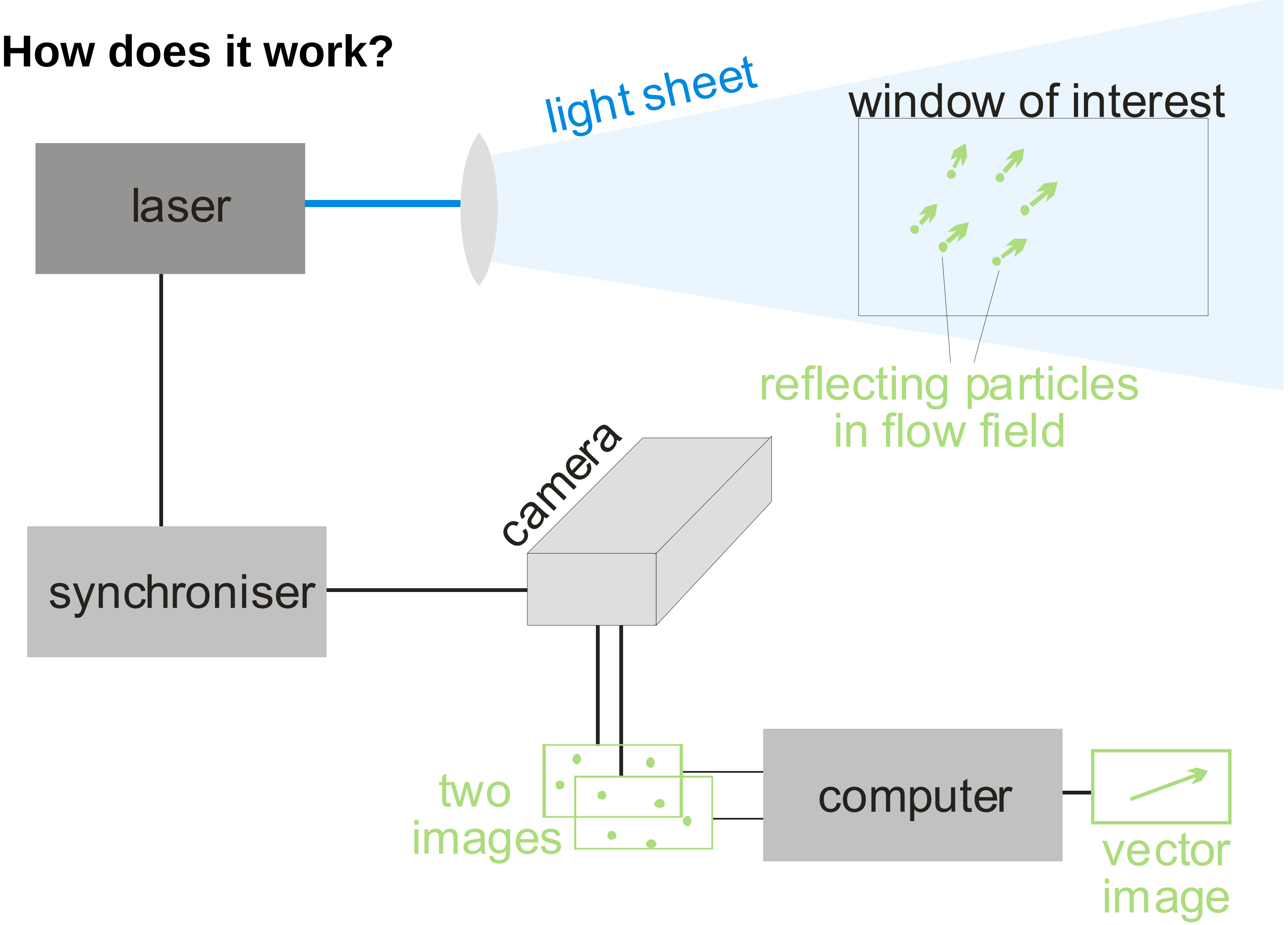
Schematic of a typical Laser-Doppler system



4. Particle image velocimetry

Application: flow visualisation

How does it work?



light sheet

window of interest

laser

reflecting particles in flow field

camera

synchroniser

two images

computer

vector image

Madras experiments ppt12.cdr

Fluid is seeded with tracer particles.

Light sheet is created from laser and positioned to intersect the fluid.

→ The tracer particles reflect light.

Synchroniser triggers laser pulse and camera.

→ A series of 2-D images are produced.

Image analysis

This is done with image pairs and based on a statistical approach.

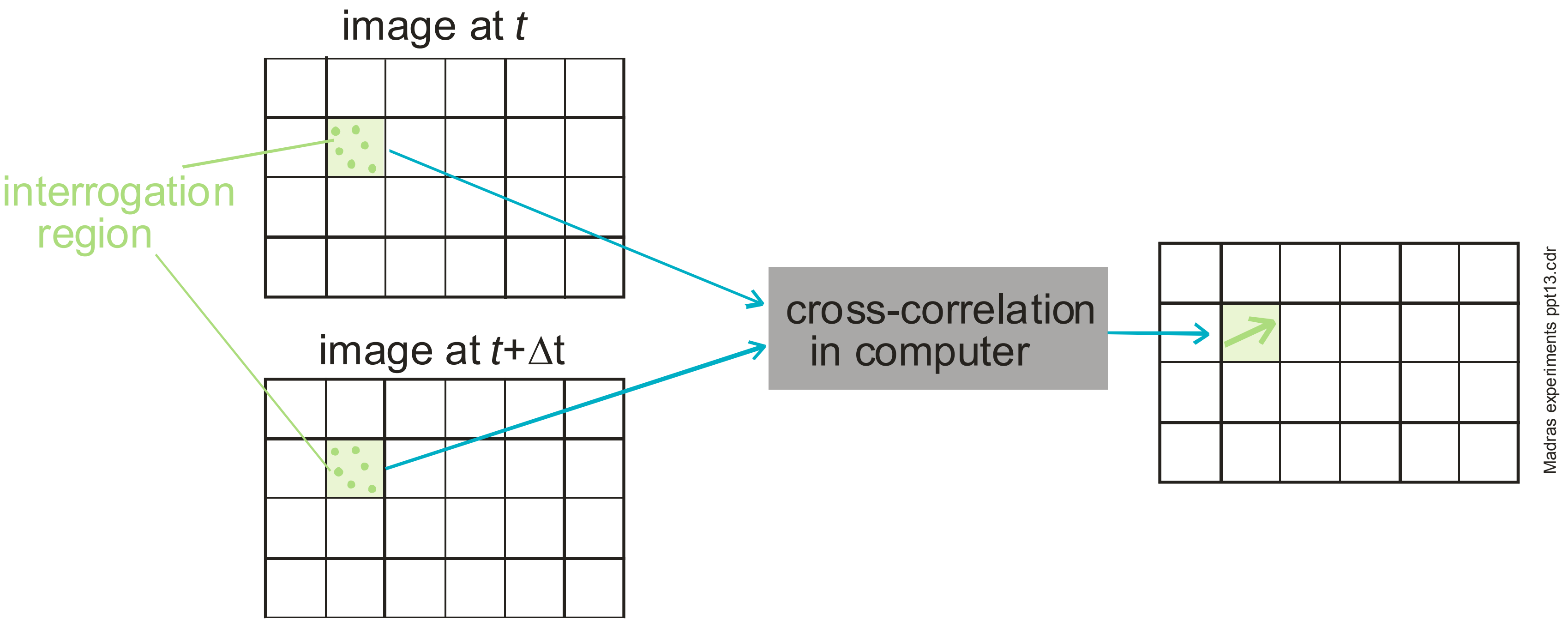


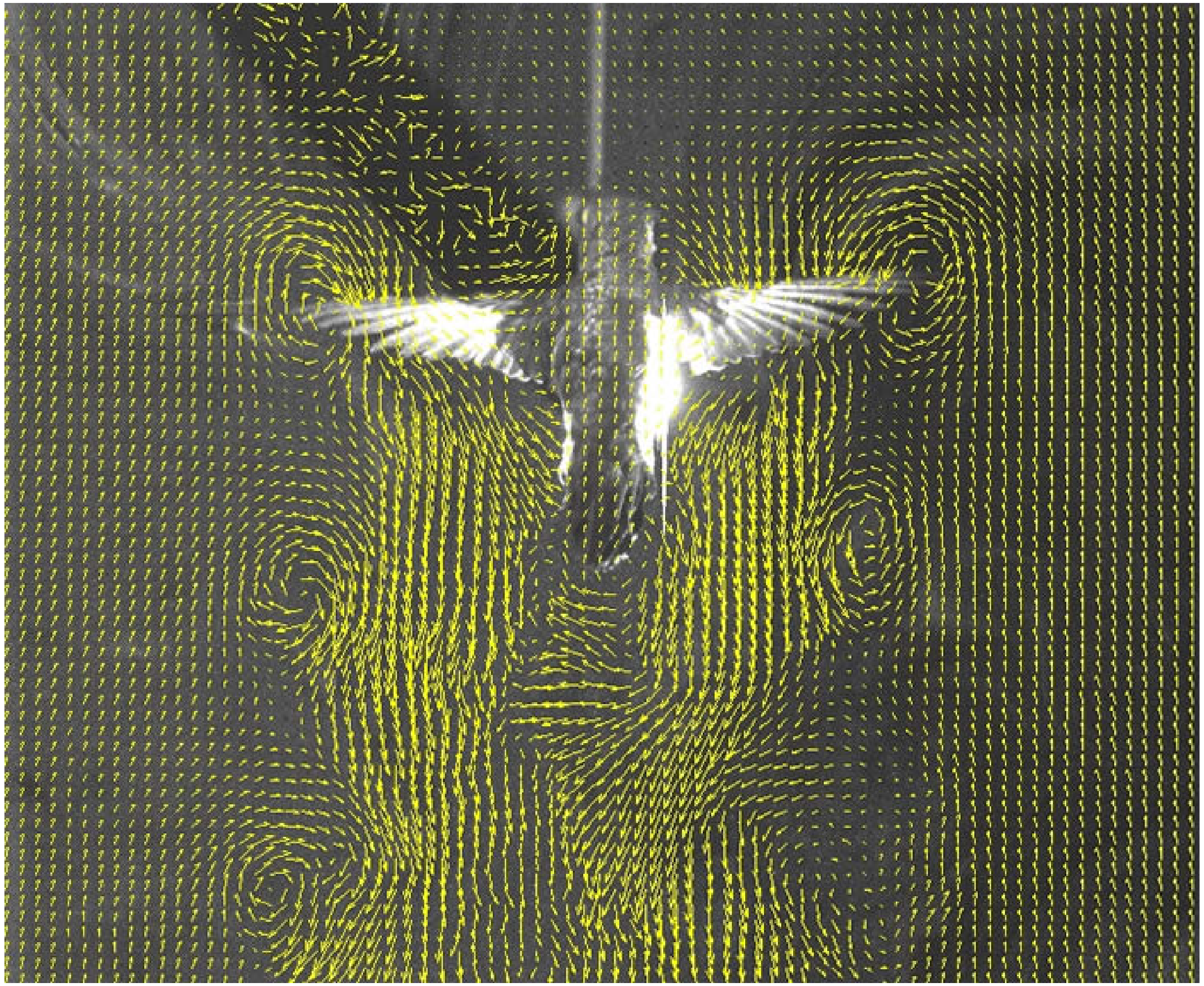
image is subdivided into cells (“interrogation regions”)
cross-correlation of individual cell pairs

→ average displacement vector within cell

repeated for each cell pair → map of velocity vectors

There is no tracing of individual particles → fast analysis

Example: Airflow in the wake of a flying bird
(note the vortices created by the wing tips)



from: http://dbs.umt.edu/flightlab/ParticleImageVelocimetry.htm

Advantages

simultaneous measurement of entire cross-section of flow field

minimal intrusion (seed particles have same mass density as fluid)

Potential problems

expensive equipment

tracer particles may not follow flow dynamics

5. Summary of applications

Chemiluminescence:	global rate of heat release local rate of heat release (line-of-sight)
LIF:	equivalence ratio flame structure rate of heat release fuel distribution
LDA:	velocity of fluid particles (local)
PIV:	velocity of fluid particles (whole cross-section)