LUND UNIVERSITY

Combustion Laser Diagnostics

Lectures presented

By Professor Marcus Aldén, LU

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by

Professor Marcus Aldén, LU

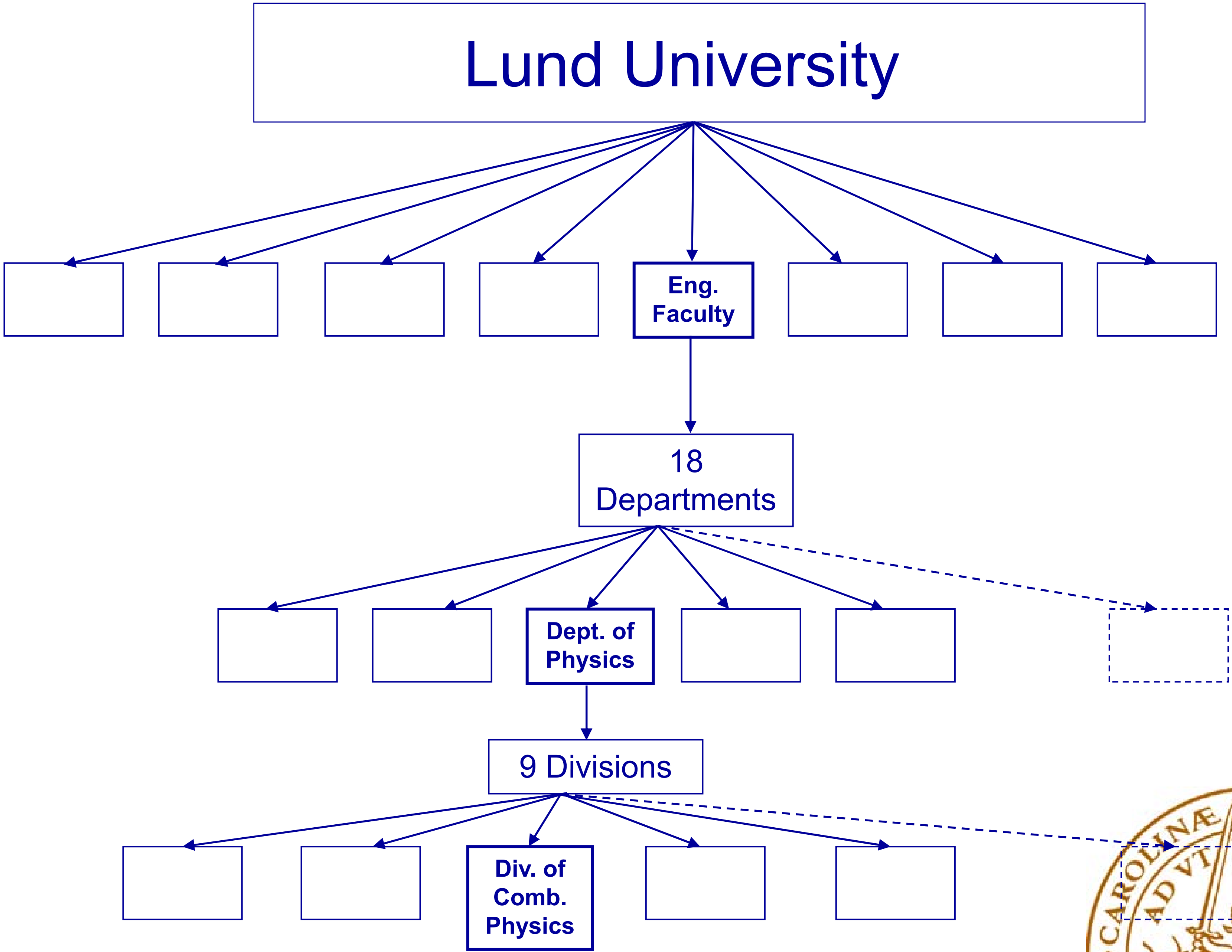
Background

Lund – the City

- A creative crossroads with a down-town area dominated by history
- Founded in the late 10th century
- A leading religious, academic and cultural centre in all of Scandinavia in the 12th century
- Became Swedish in 1658
- 100,000 inhabitants – half of them with ties to the University

One of Europe's Leading Universities

- Founded in 1666
- 38 000 students
- 2 300 postgraduate students
- 5 200 employees
- 560 professors (16 % women)
- Eight faculties
- Several campuses
- 5 300 SEK million turnover


Lund University
Eng. Faculty
18 Departments
Dept. of Physics
9 Divisions
Div. of Comb. Physics

Division of Combustion Physics

Main research areas

- Combustion diagnostics
- Chemical kinetics

Economy

- ca 10 % faculty resources
- ca 90 % external resources (STEM, VR, EU, MISTRA, Wallenberg, SSF, industry).

Approximate budget: 27 MSEK/year

Courses

- Fundamental Combustion
- Laser-based combustion diagnostics
- Molecular spectroscopy

Personal

- 3+1 professors (fulltime/adj)
- 4 ass. prof (docents)
- 4 post.doc
- 3 T/A
- 19 doctorate students

Examination (since 1991)

- 44 PhD
- 18 Tekn. Lic

Division of Combustion Physics

- Participating in ~ 6 European projects
- Truly world unique intrumentation:
  - ~6 complete Nd:YAG/ dye lasers, 2 Multi:YAG laser clusters, OPO laser, single mode Alexandrite laser, picosecund laser, 2 DFDL, femtosecund laser, LDV, PIV
  - ~6 ICCD's, 2 framingcameras, 1 streakcamera
- Several burners; laminar, turbulent, atmospheric-high pressure

Marcus Aldén - Short CV

- Diploma work for M.S in laser diagnostics 1977
- U.S visit to G.E R&D Centre, 1978/79
- PhD in laser diagnostics of combustion proc. 1983
- Professor in combustion laser diagnostics, LU 1991
- Chairman GRC laser diagnostics of comb. proc. 2003
- Program co-chair of CI Symp. 2006
- Vice president CI, 2010
- Invited talk at the CI Symp. 2004, 2010

Member of Swedish Royal Academy of Science, KVA

Member of Swedish Royal Academy of Engineering Sci., IVA

Course outline

- Hour 1: Introduction to combustion laser diagnostics, definitions
- Hour 2: Molecular spectroscopy: Definitions, rotational, vibrational, electronic structures
- Hour 3: Laser diagnostic instrumentation: Lasers, detectors, optical components
- Hour 4: Semi intrusive techniques: LII and LIBS
- Hour 5: Laser-induced fluorescence: Introduction/theory, basic definitions
- Hour 6: Laser induced fluorescence: Applications - engines, gasturbines, furnaces
- Hour 7: Rayleigh scattering: Introduction, potential, limitations, filtered Rayleigh Scattering
- Hour 8: Raman scattering: Basic theory, thermometry, species concentration measurements
- Hour 9: Surface thermometry: Thermographic phosphorescence – definitions, applications
- Hour 10: Non-linear techniques I: CARS Spectroscopy – Theory, definitions, applications
- Hour 11: Non-linear techniques II: Polarization spectroscopy and Degenerate four-wave mixing – Theory, potential, applications
- Hour 12: New techniques for future challenges:
  - "New" species detection
  - Single ended experiments - ps Lidar, Structured illumination
  - Measurements in optical dense media (sprays) - Ballistic imaging, SLIPI

Motivation for combustion research

By an improved fundamental understanding of combustion processes there will be a potential to;

- Improve efficiency

  lower fuel consumption

- Reduce emissions

  NO_x, SO_x, particles, CO_2 ,,,

- Improve reliability

  increased competiveness

- Develop combustion on alternative fuels and new technology

  hydrogen combustion, biomass, syngas

- Improve safety

  suppress fire initiation and spread

Combustion situations/applications

For specified tasks

Candle light
Welding flame
Bunsen burner
Log fire
Liquid gas stove

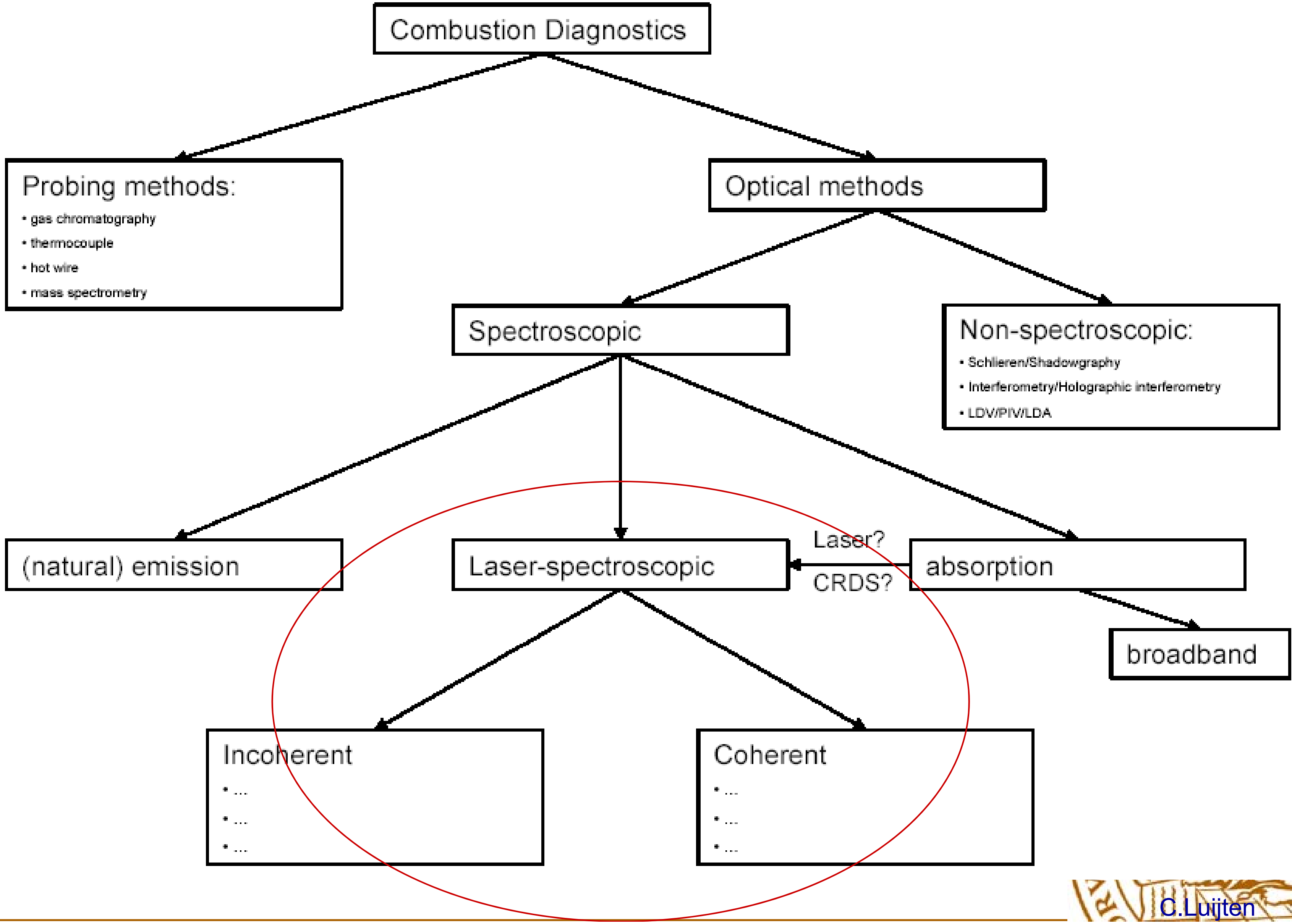
Unwanted events

Fire
Explosion
Detonation

For efficiency, reliability and low emissions

Furnace
Fluidised bed
Diesel engine
Gasoline engine
Rocket engine
Jet engine
Gas turbine

1. Combustion diagnostics



Short history: Combustion Laser Diagnostics

- First papers on combustion applications in the early seventies; Raman/Rayleigh applications
- First conference in 1974 in Schenectady, NY
- 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-

Suitable reading:

- A.C. Eckbreth, Laser Diagnostics for Combustion Temperature and Species, 2nd edition. Gordon and Breach, UK, 1996.

- K. Kohse-Höinghaus, J.B. Jeffries (Eds.), Applied Combustion Diagnostics. Taylor and Francis, New York, 2002.

- K. Kohse-Höinghaus, R. S. Barlow, M. Aldén and J. Wolfrum, “Combustion at the focus: laser diagnostics and control”, Comb Inst, 30 (2005) 89-123.

- M. Aldén, J. Bood, Z-S Li and M. Richter, Visualization and understanding of combustion processes using spatially and temporally resolved laser diagnostic techniques, Comb Inst, 33 (2011) 66-97

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)

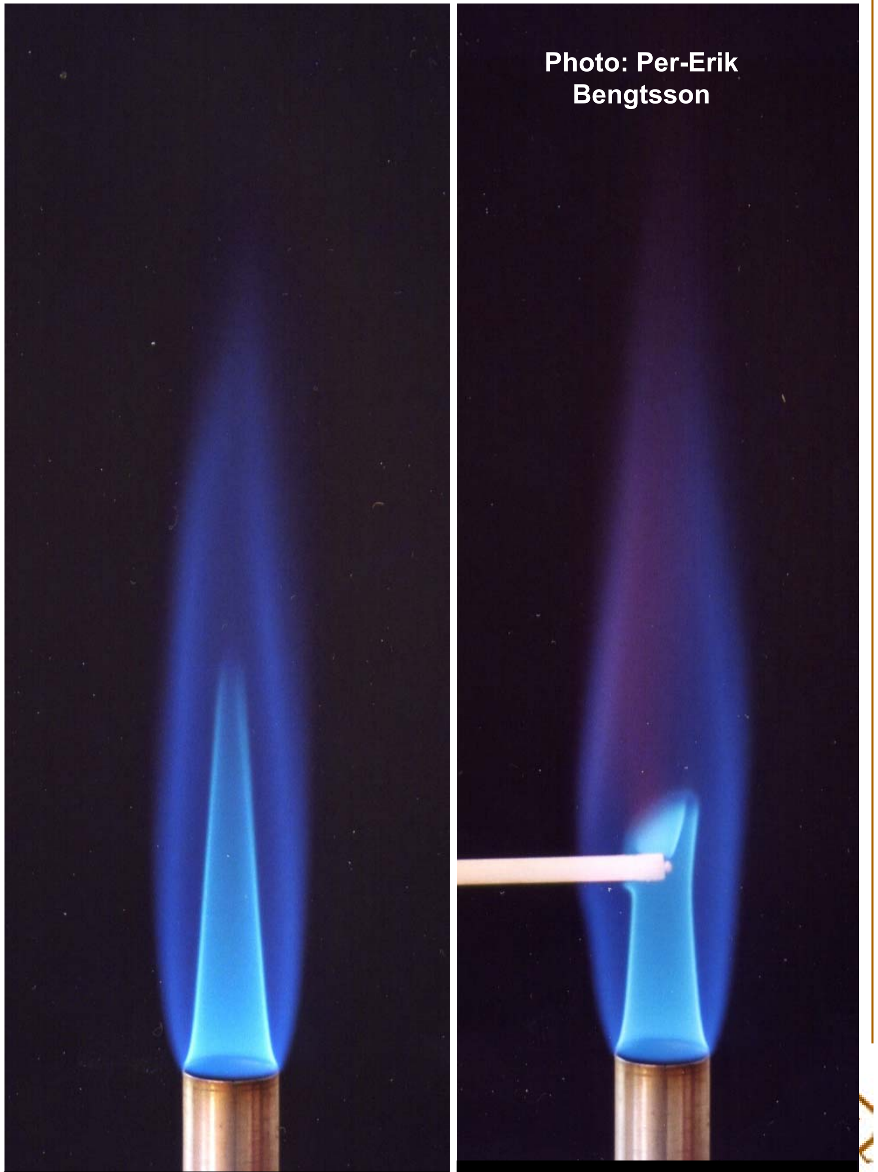
- Applications of the more developed techniques for measurements of relevant parameters, e.g. species concentrations, temperatures, velocities and particle characteristics for phenomenological studies (e.g investigations of turbulent combustion)

- Applications of mature techniques for characterisation, optimisation and control of industrial processes (e.g investigations of IC engine performances)

Probe techniques

Advantages:	Disadvantages:
• Relatively cheap (some) • Robust and easy to use (some) • Do mostly give quantitative results (correct?) • Can measure larger molecules	• Intrusive • May be difficult to estimate measuring errors • Do not easily measure atoms and radicals • Often low (unclear) temporal and spatial resolution

Examples of intrusivness of a probe



Undisturbed pre-mixed flame

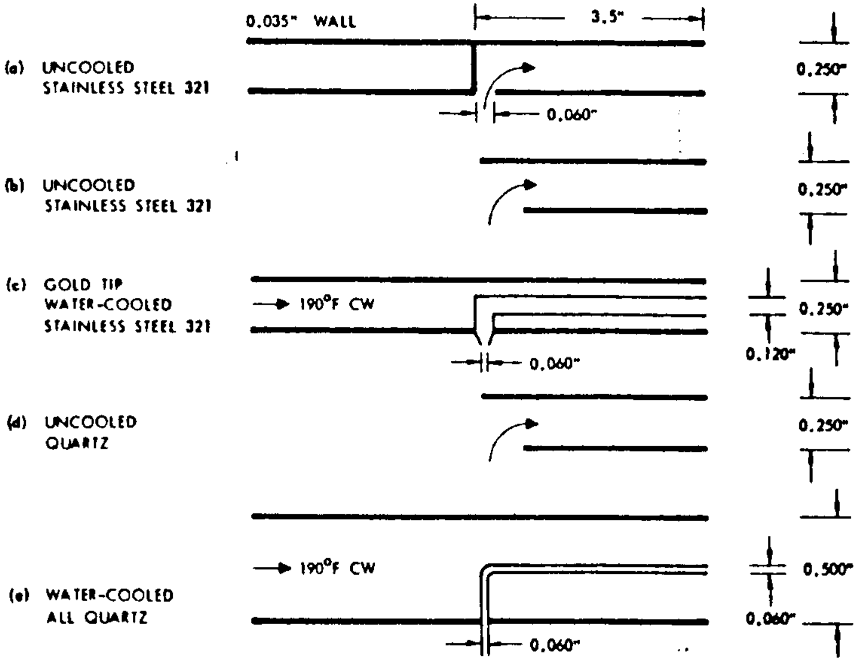
Premixed flame disturbed by a thermocouple

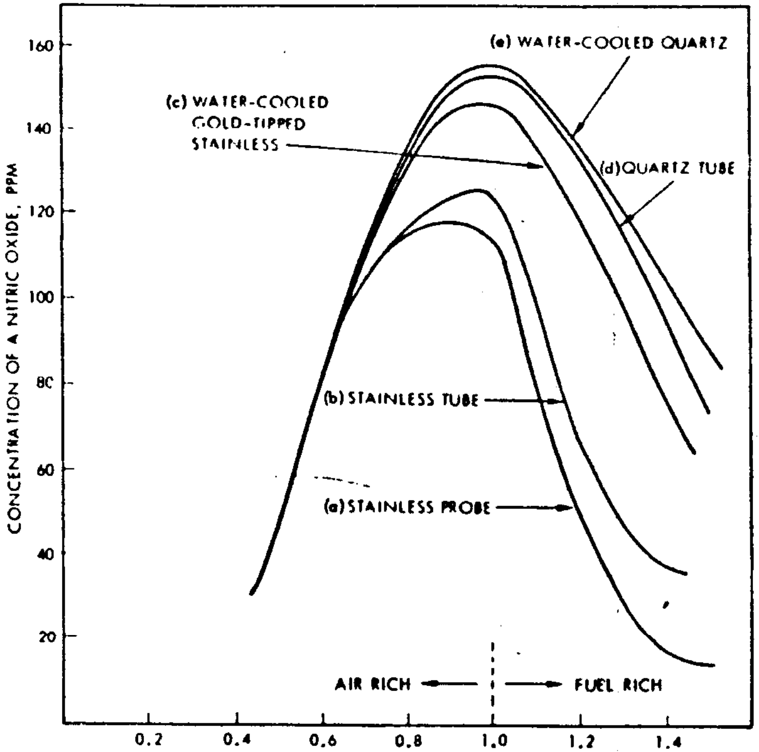
Possible disturbances during probe (extraction) measurements

- **Aerodynamic effects**
- **Effects of concentration gradients**
- **Thermal effects**
- **Catalytic effects**
- **Quenching effects**

A general reference: M. V Heitor and A.L.N. Moreira ”Thermocouple and sample probes for combustion studies”, Prog. Energy and Comb. Sci. 19, 259 (1993)

Example on probe influences on NO measurements





C. England, et al., Comb. and Flame 20, 439 (1973).

Optical techniques

Advantages:	Disadvantages:
• Non-intrusive with high temporal/spatial resolution (laser techniques) • Can measure simultaneously in many points • Simple (not laser techniques!)	• Mostly expensive and complicated equipment, theory (laser techniques) • May have difficulties to give quantitative data

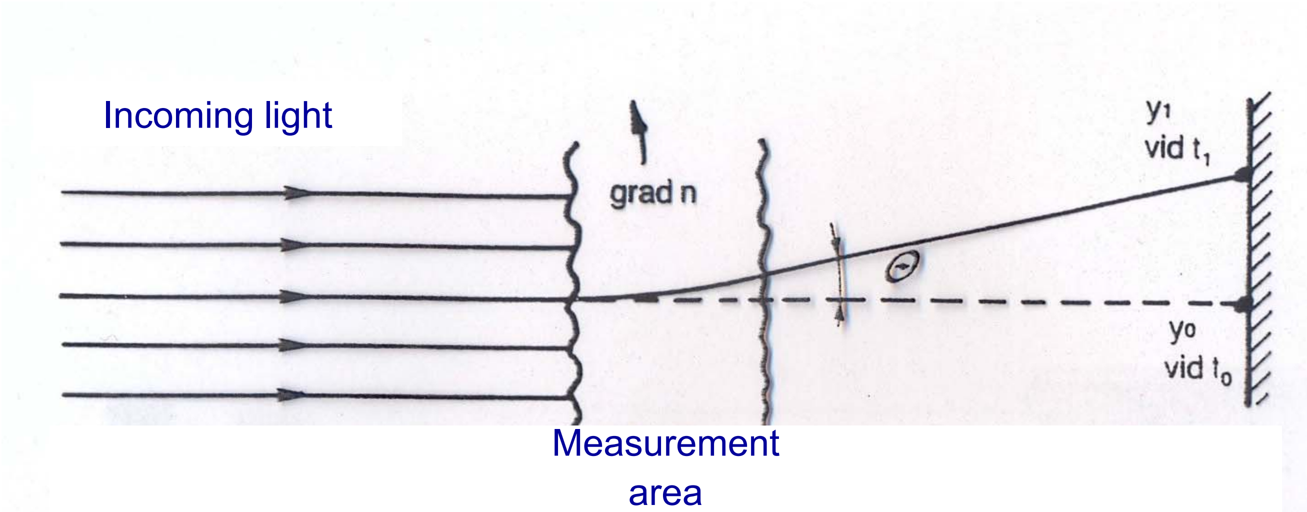
Non-spectroscopic optical techniques

- **Refractive index techniques**
- **Laser doppler velocimetry, LDV**
- **Particle induced velocimetry, PIV**

Refractive index techniques

(Interferometry, shadography, schlieren techniques)

Referens: *Optics of flames* by F.J. Weinberg (Butterworths London 1963)

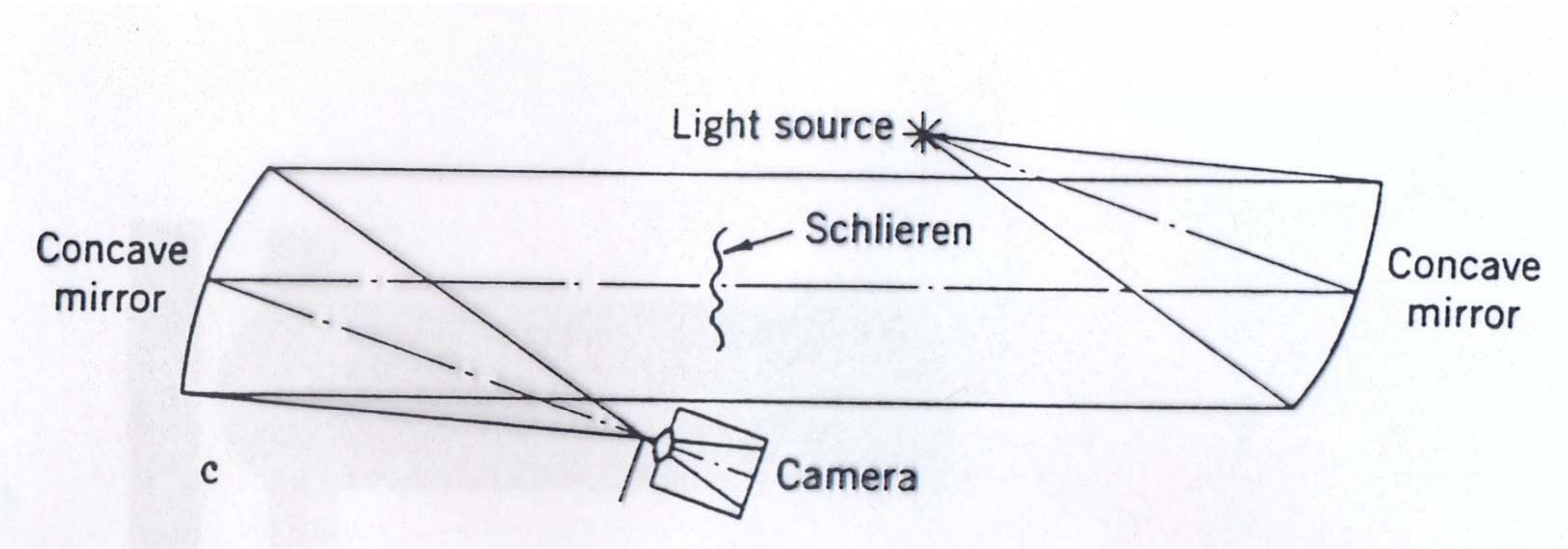


Shadography measures; $y_1 - y_0$

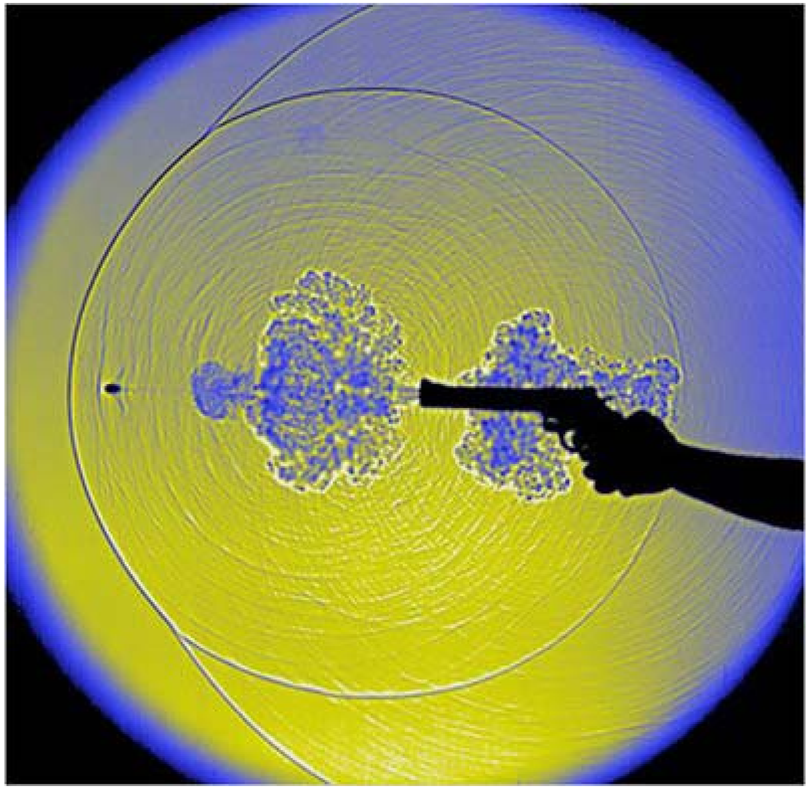
Schlieren measures; Θ

Interferometry measures; $\dfrac{2\pi (t_1 - t_0) c}{\lambda}$

Set-up schlieren/shadography



Some examples from the web



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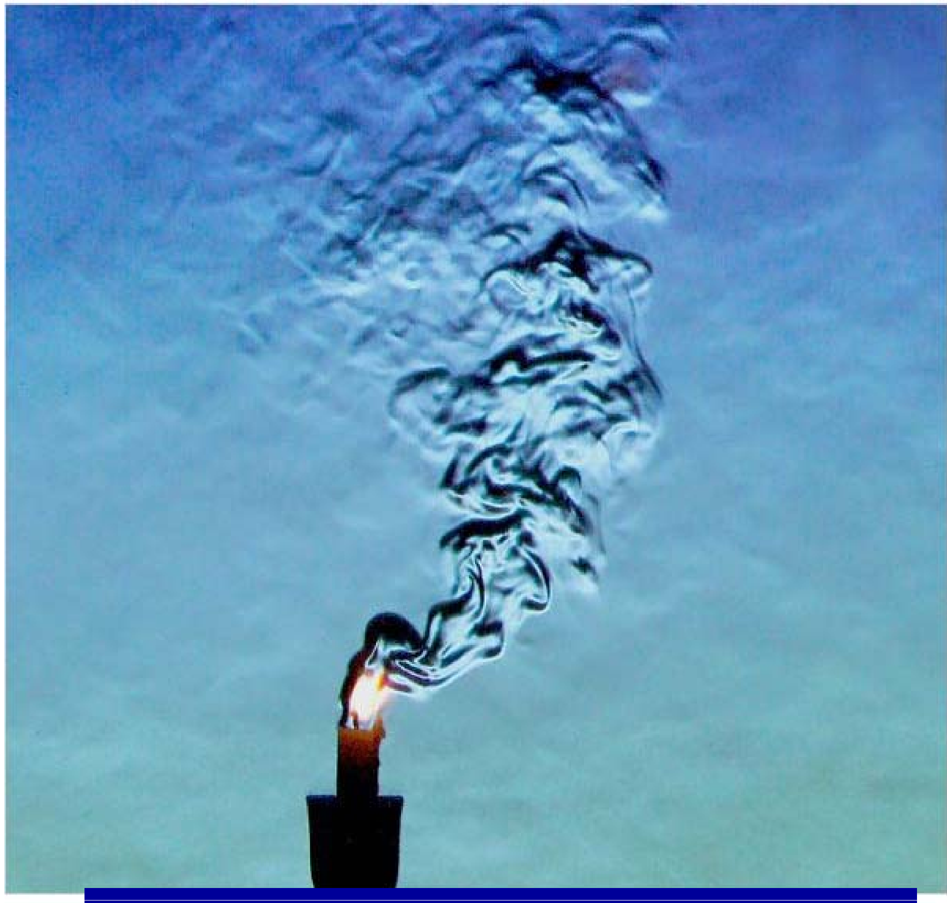

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Laser doppler velocimetry, LDV

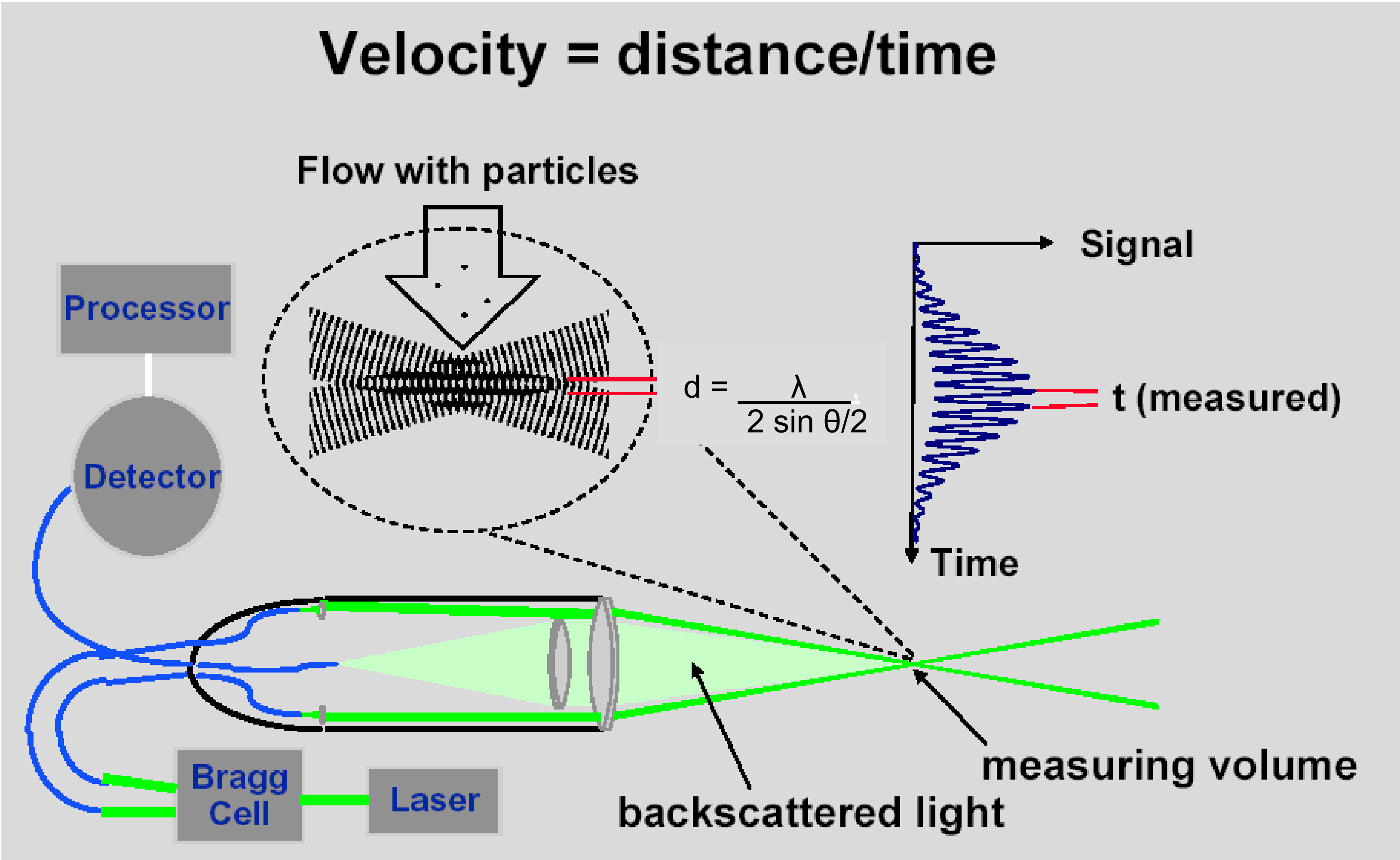
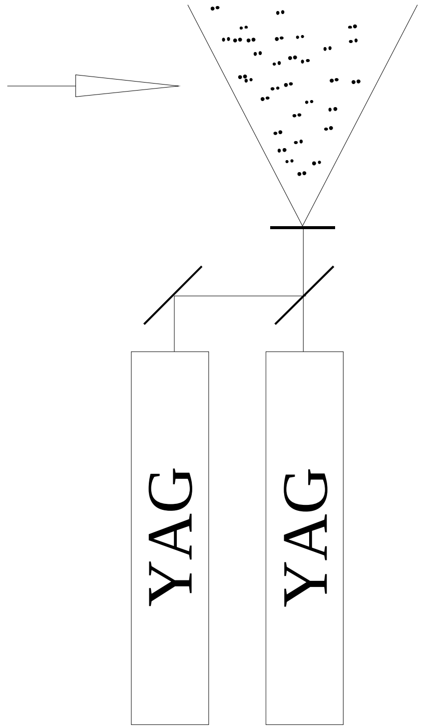


Image from
www.dantec.com

Particle Image Velocimetry, PIV

- PIV is capable of simultaneous velocity measurements at many points in a plane.
- PIV involves the illumination of a plane of the flow under investigation with two thin, pulsed sheets of light. The flow is seeded with particles
- The light scattered from the particles and from successive pulses are being recorded either on film or a CCD array, forming a multiple exposure of each particle image. If the time between the pulses is known, velocity can be determined as the ratio of the particle displacement and the elapsed time



PIV, principles

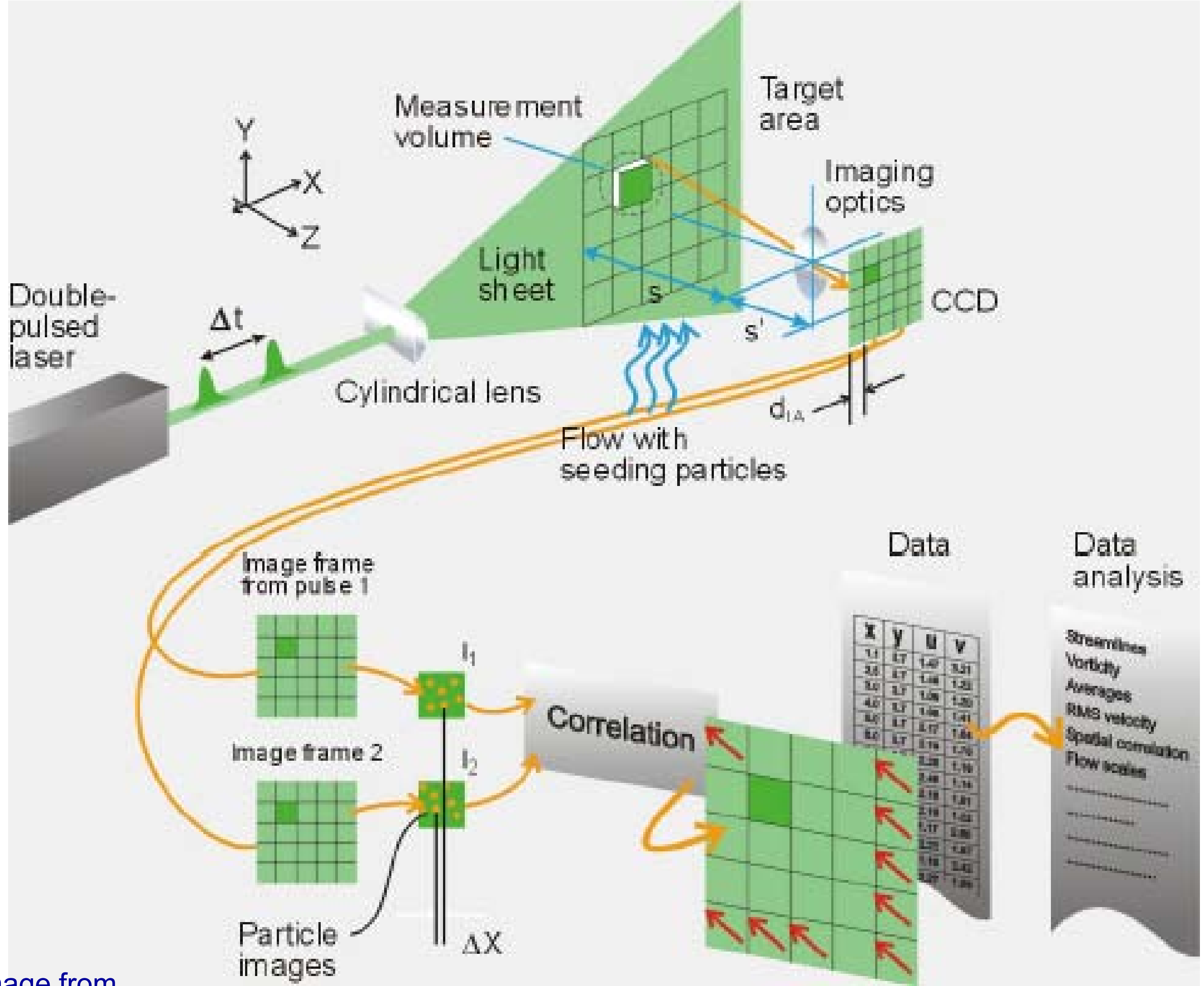


Image from
www.dantec.com

Comparison of velocity measurements

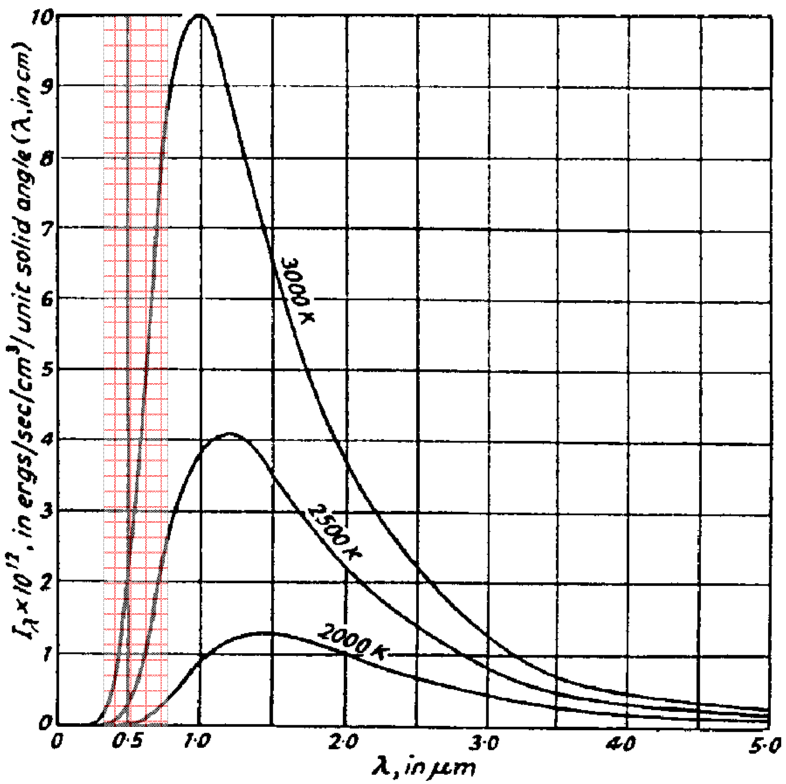
PIV:

- Instantaneous velocity vectors in a plane
- Correlation within interrogation area reduces spatial resolution, mean velocities only
- Large amount of data in limited measuring time
- High number density of seeding required

LDA:

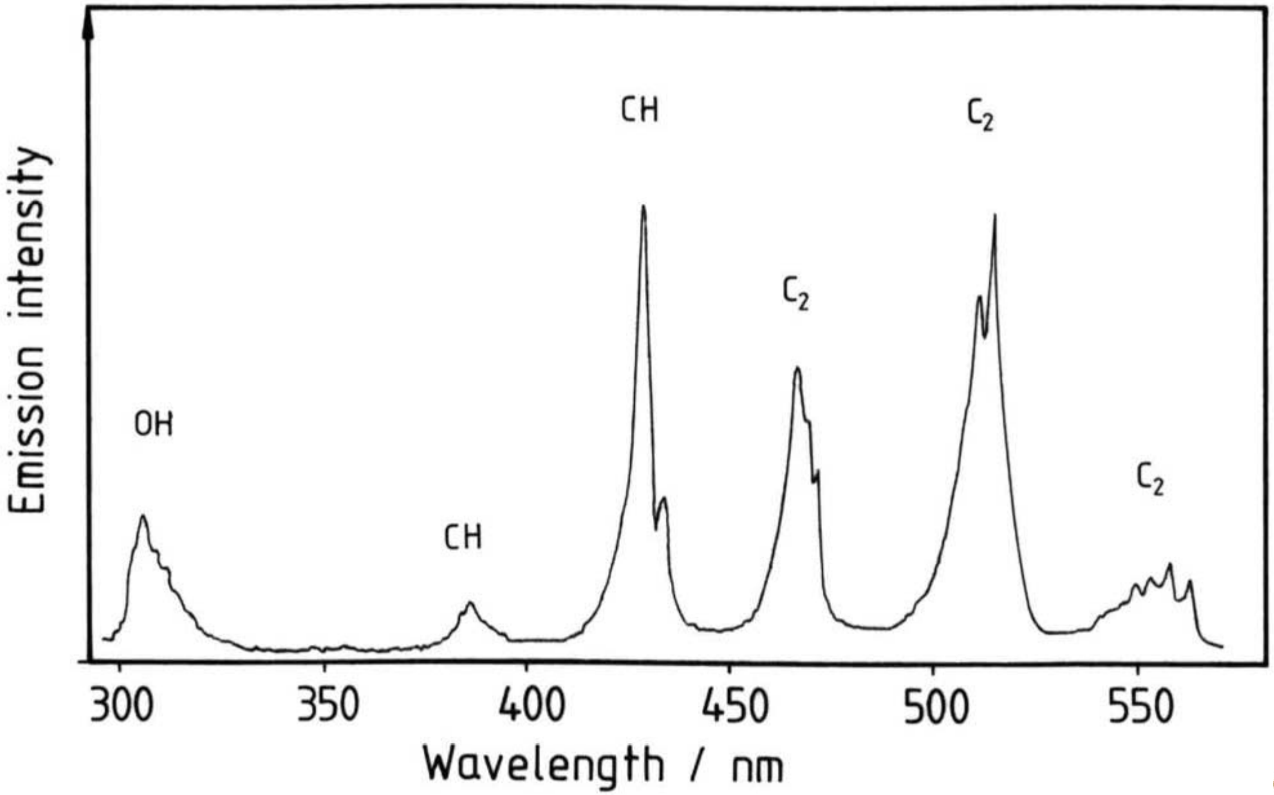
- Measures time series of velocity in a point
- High spatial resolution, suitable for turbulence investigations
- Measurement of entire flowfield time consuming
- Particles arrive randomly, data is not time equidistant

Emission spectroscopy 1: Planck radiation



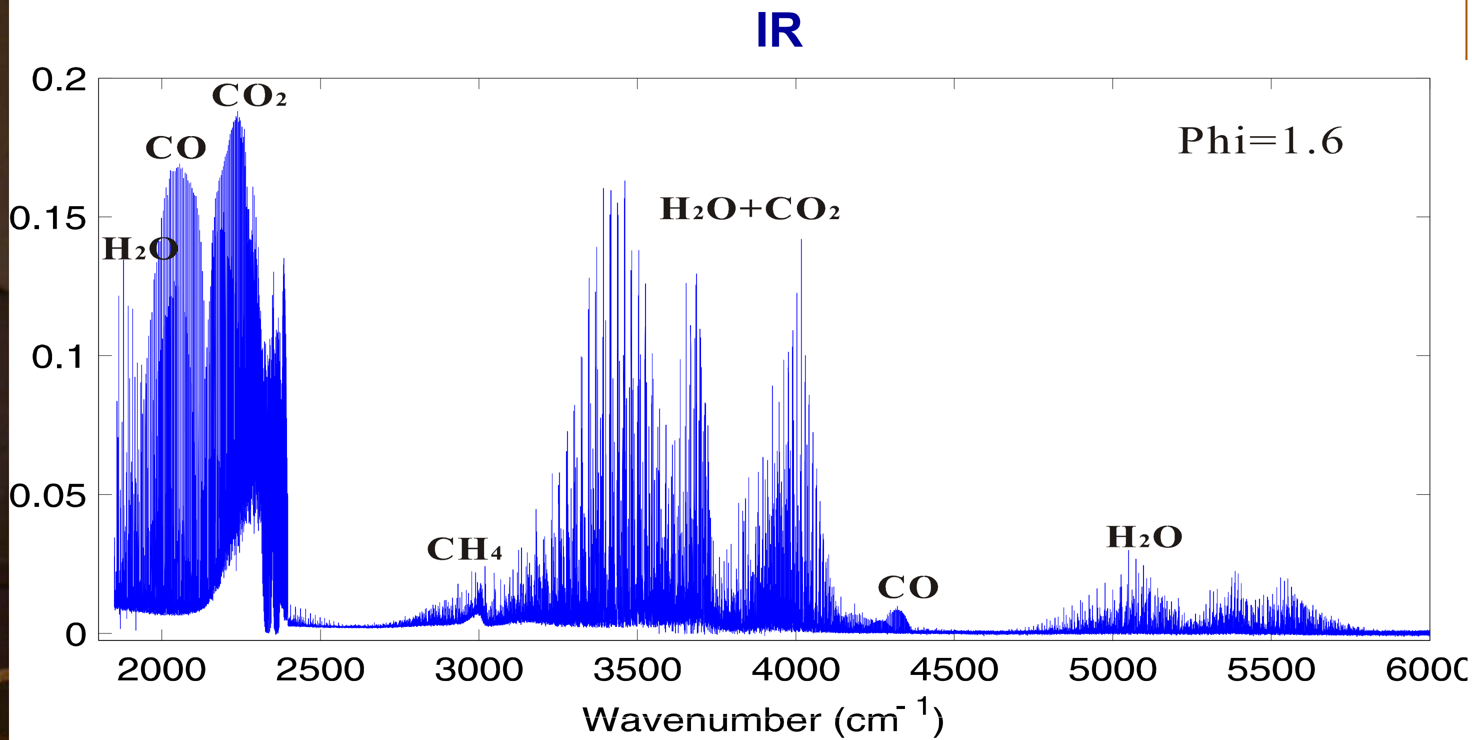
Emission spectroscopy 2: Chemiluminiscence

UV/visible



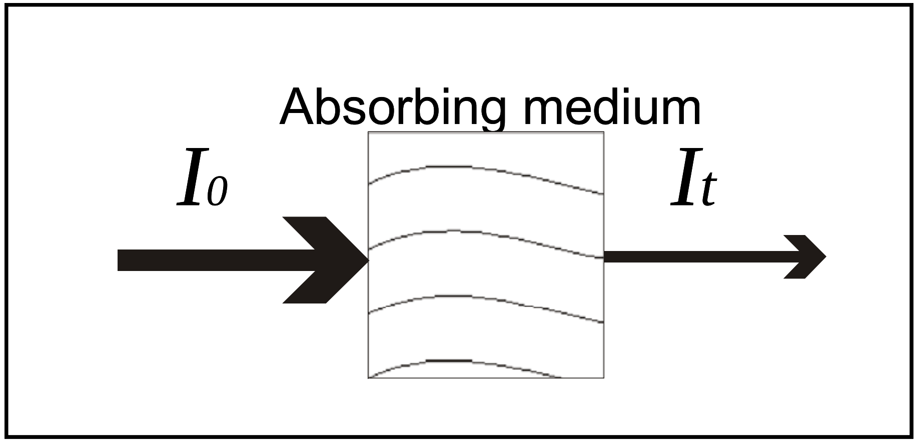
- Line of sight
- Qualitative inf.

Emission spectroscopy 2: Chemiluminiscence



- Line of sight
- Qualitative inf.

Absorption spectroscopy

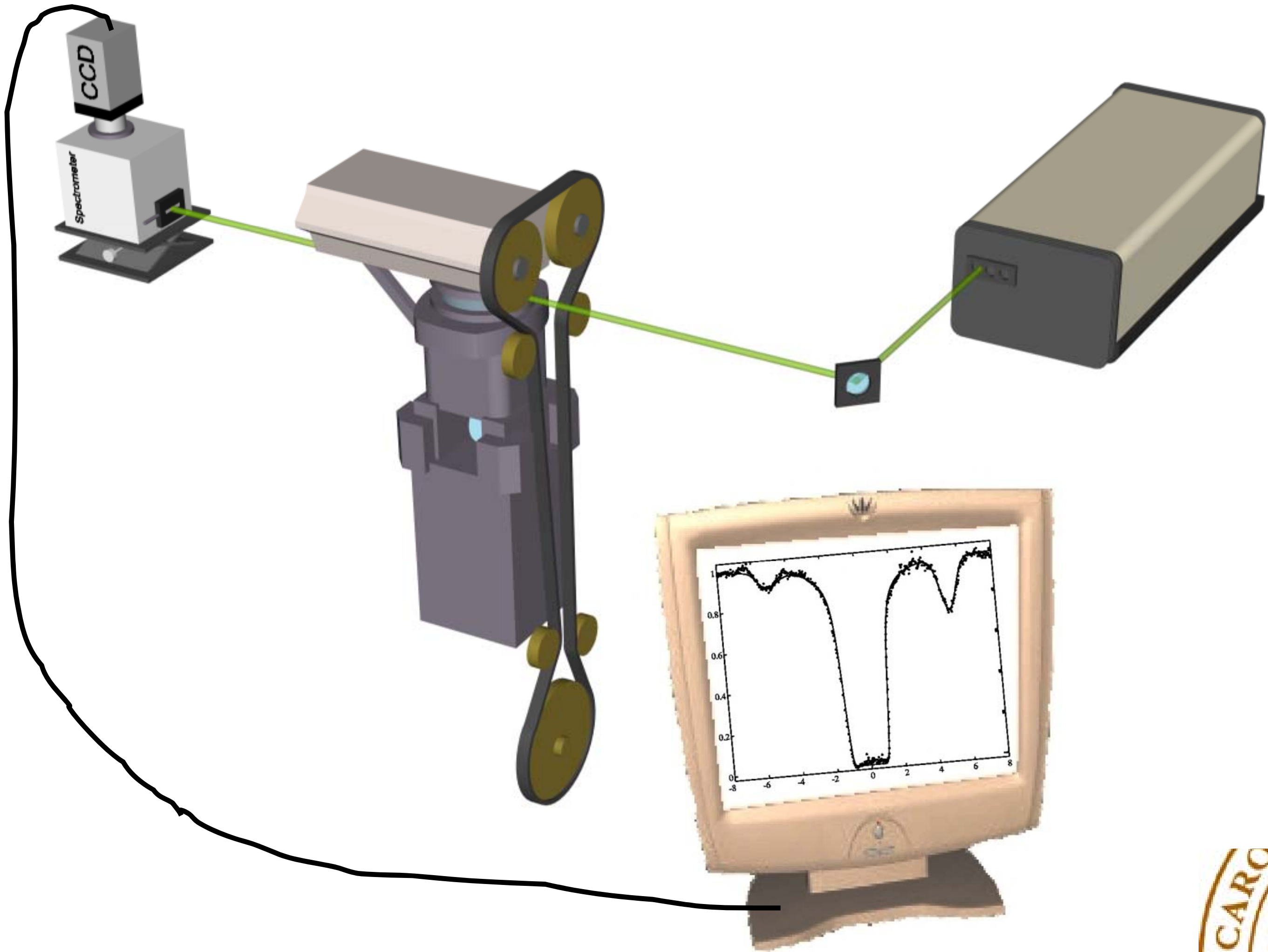


- $I_t = I_0 \exp -(N \sigma L)$

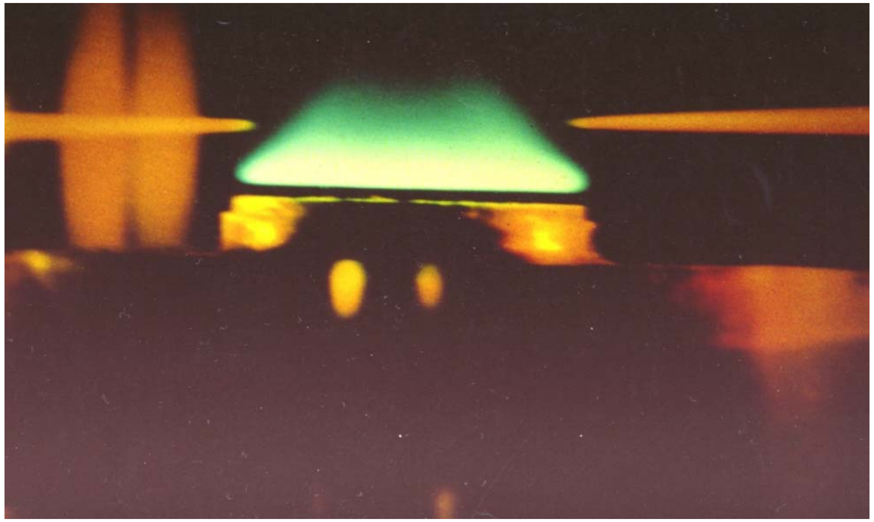
•**Line of sight**

•**Quantitative information**

Absorption measurement



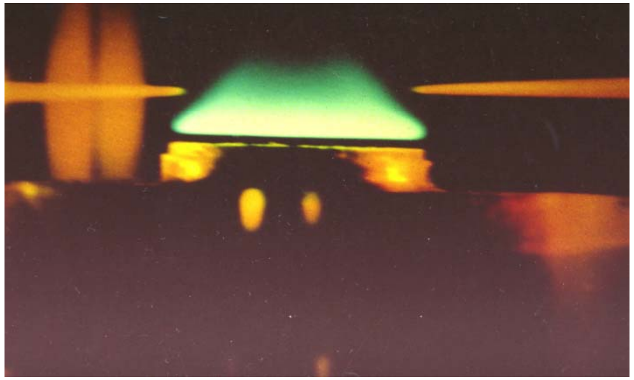
Why lasers in combustion diagnostics ?



- 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 (LIBS!)
  - Creation of molecular fragments; atoms
  - Optical pumping

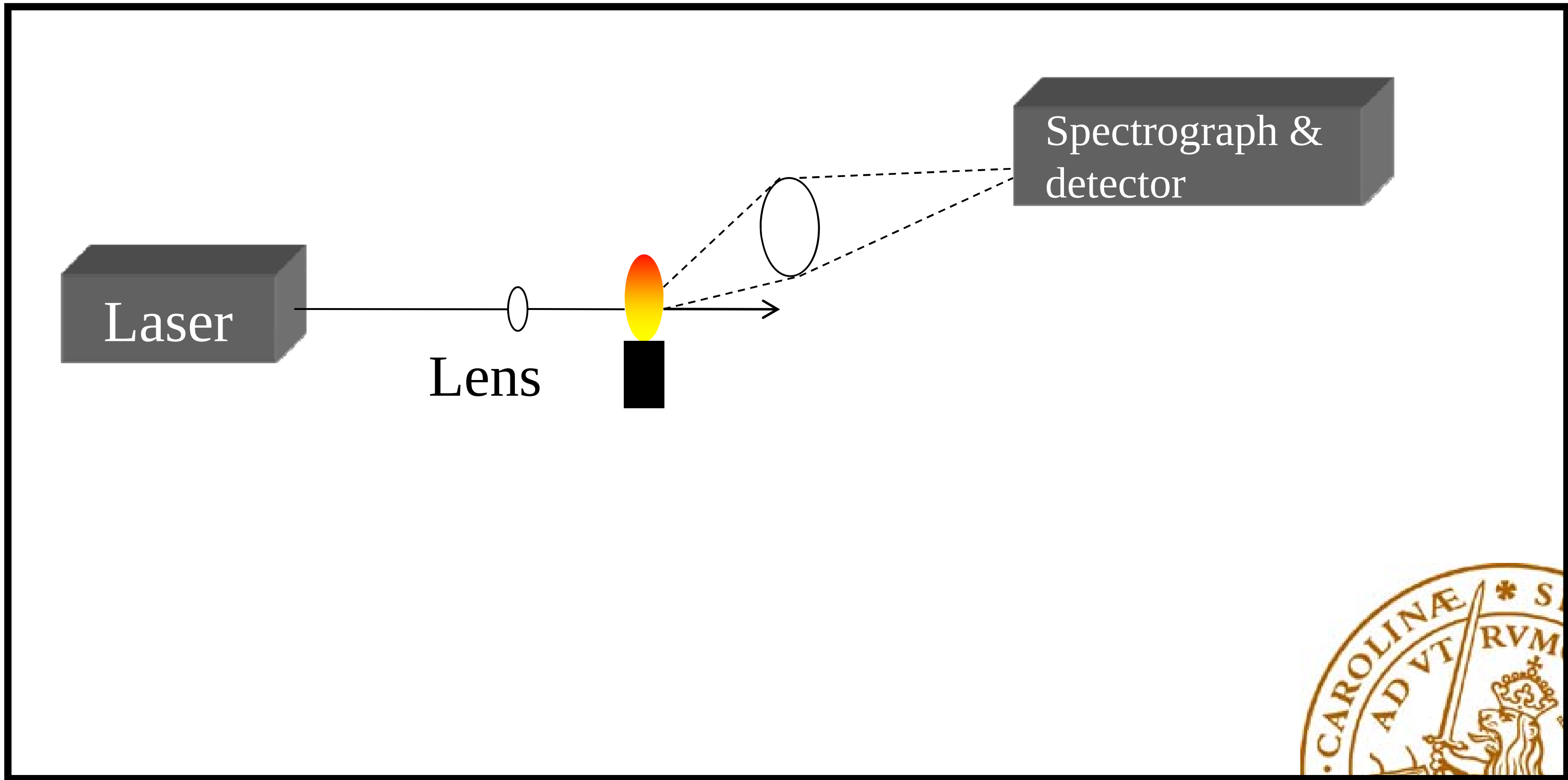


Laser diagnostics in combustion

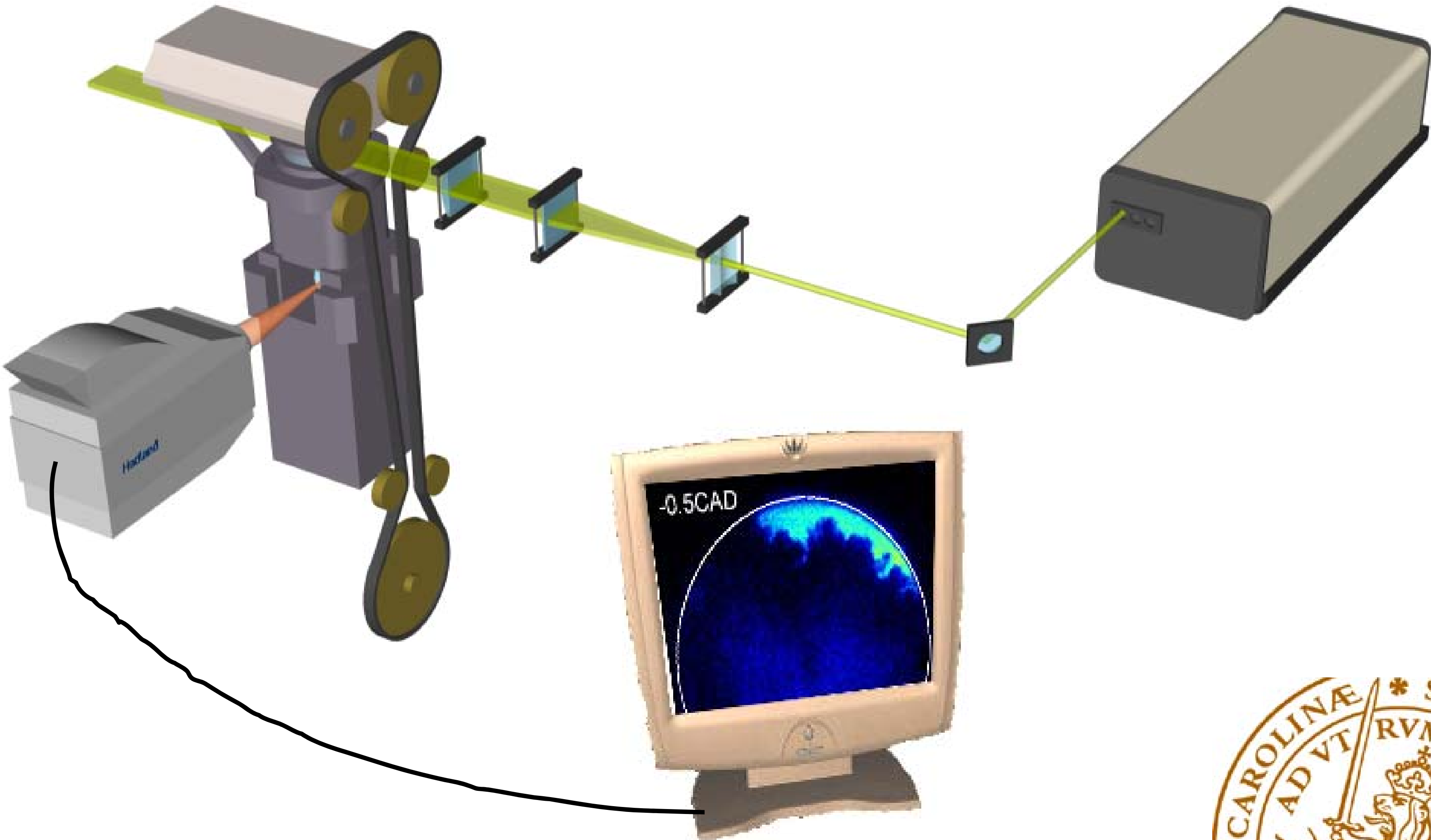
What can be measured ?

- 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

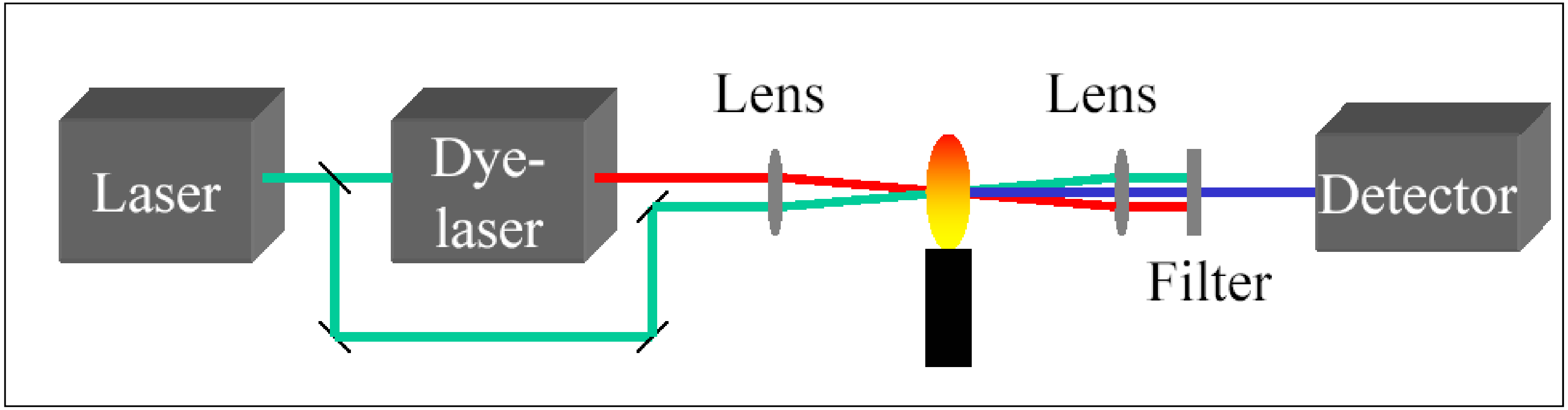


Laser techniques

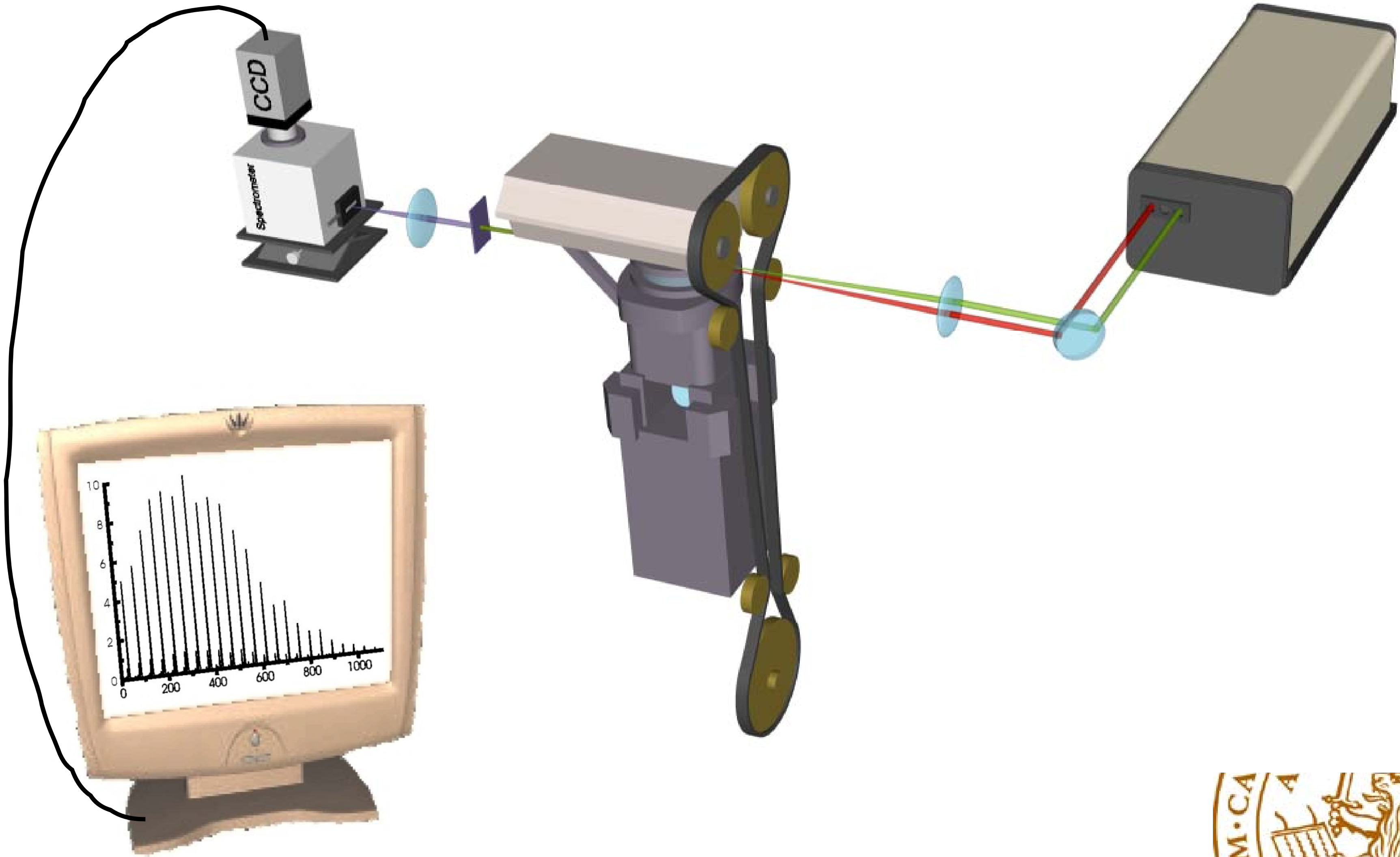
Incoherent techniques:

- Mie/Rayleigh scattering (incl. LDV, PIV)
- 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