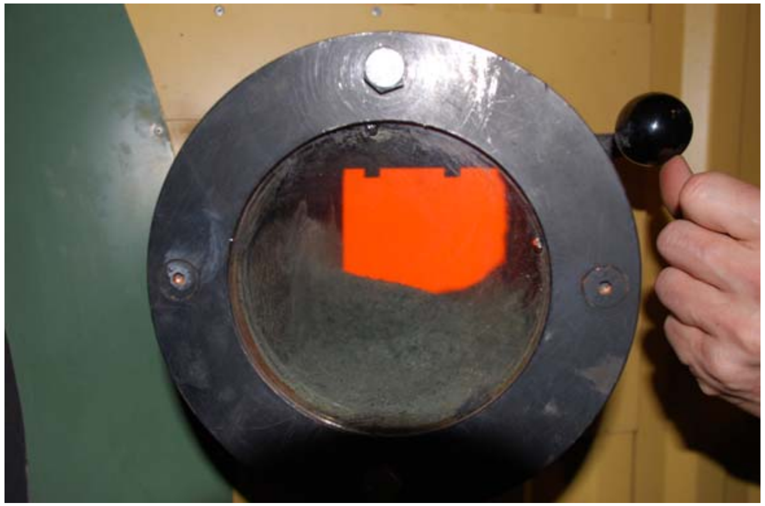
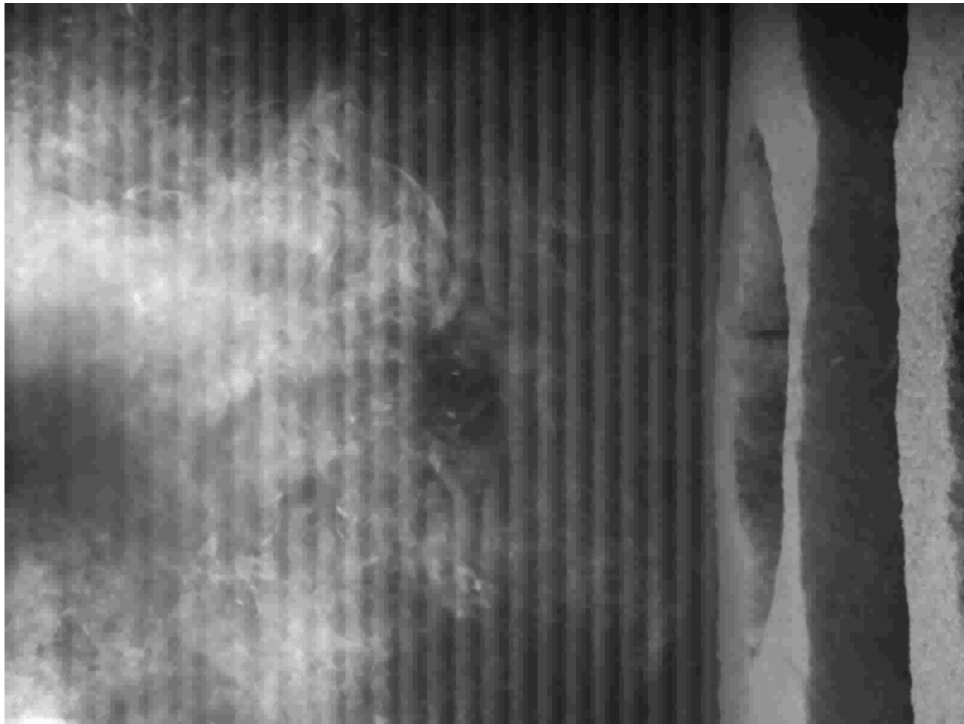
12. New techniques

- **Measurements in areas with limited optical access**
  - Single ended experiments
    - ps-lidar,
    - Structured illumination
- **Measurements in optically dense environment (e.g. sprays)**
  - Ballistic imaging
  - SLIPI (Structured Laser Illumination Planar Imaging)
- **Measurements of ”new” species**
  - Photofragmentation LIF; PF-LIF

Limited optical access

Furnaces, boilers, fires



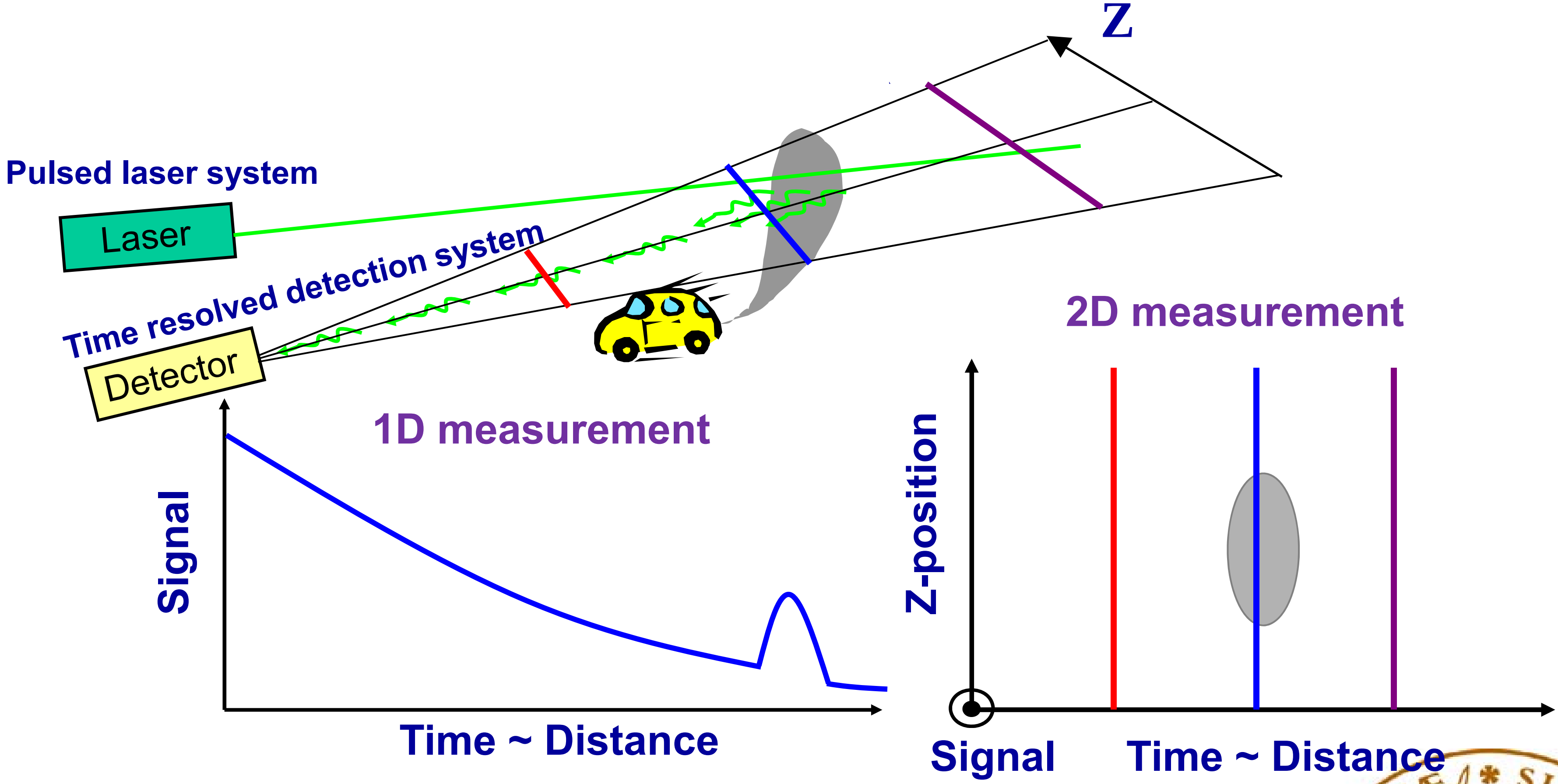


How can spatially resolved measurements be made in situations with very limited optical access?

Can a backscattered technique be developed for sub-cm resolution?

- **Potential approach: ps-LIDAR**
- **Potential approach: Structured illumination**

LIDAR concept



Courtesy: Kaldvee and Bood 2010

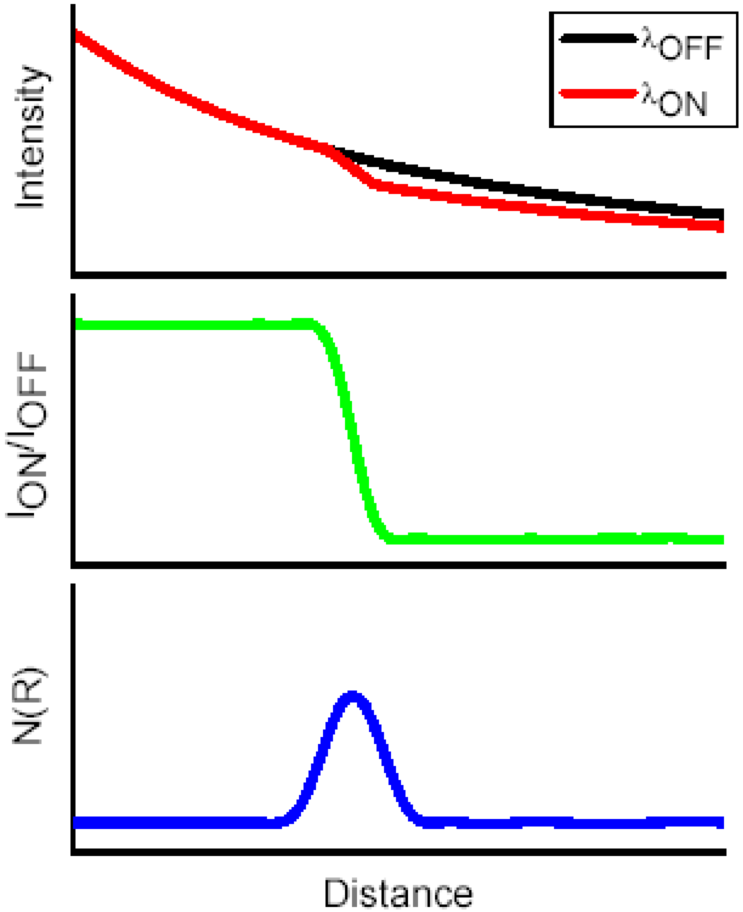
Lidar equation

$$I(\lambda,R)=DW_p(\lambda)n_b(r)\sigma_b(\lambda)\frac{\Delta R}{R^2}\exp\left(-2\int_0^R\alpha(\lambda,s)ds\right)$$

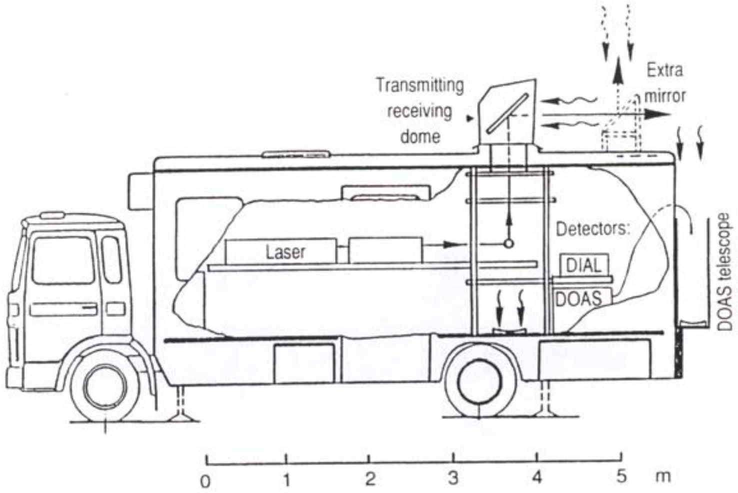
- **D is a system constant,**
- **W_p is the transmitted laser pulse energy,**
- **n_b is the number density of scattering objects,**
- **σ_b is the backscattering cross section of the scattering objects,**
- **ΔR is the range resolution of the system depending on the time between the samplings of the signal**
- **α is the extinction coefficient.**

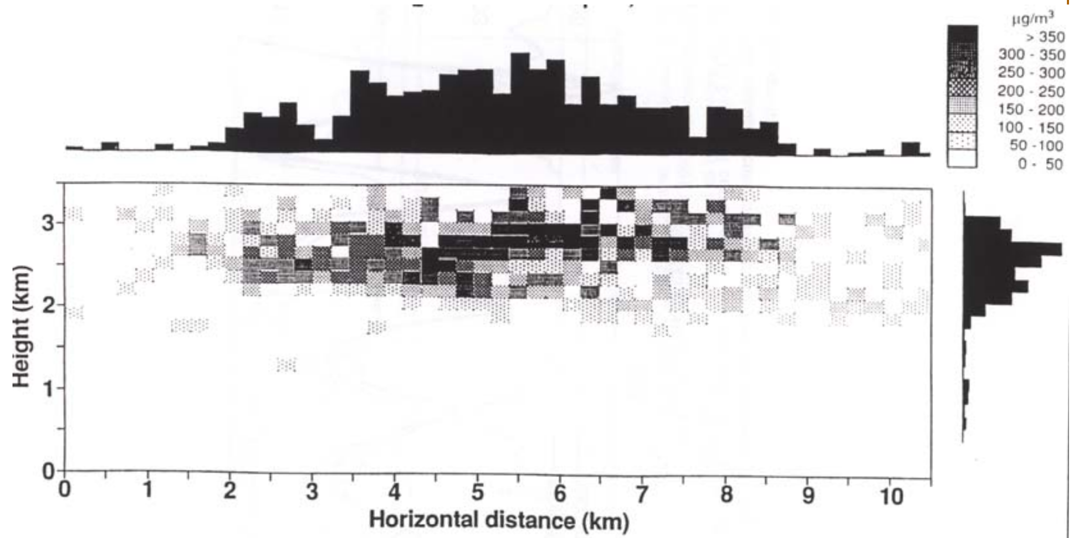
Differential Absorption Lidar (DIAL)

$$N\left(\frac{R_1+R_2}{2}\right)=\frac{1}{2(R_2-R_1)\Delta\sigma}\ln\left(\frac{I(\lambda_{ON},R_1)I(\lambda_{OFF},R_2)}{I(\lambda_{OFF},R_1)I(\lambda_{ON},R_2)}\right)$$



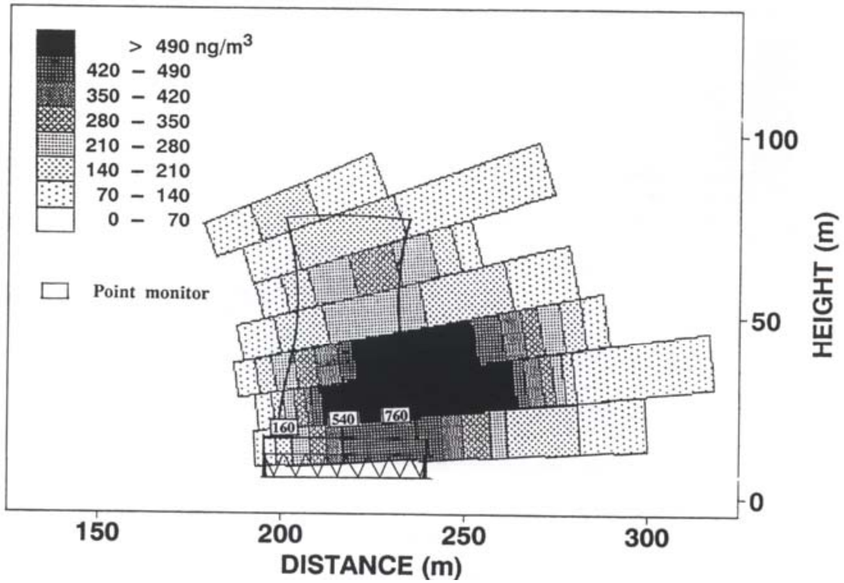
Conventional lidar 1:
SO_2 measurements at Etna

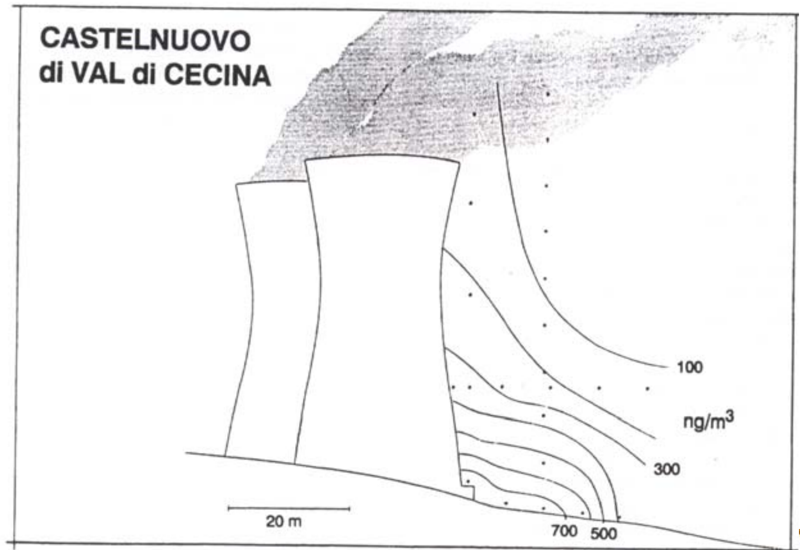




Ref: Per Ragnarsson PhD thesis

Conventional lidar 2:
Hg measurements



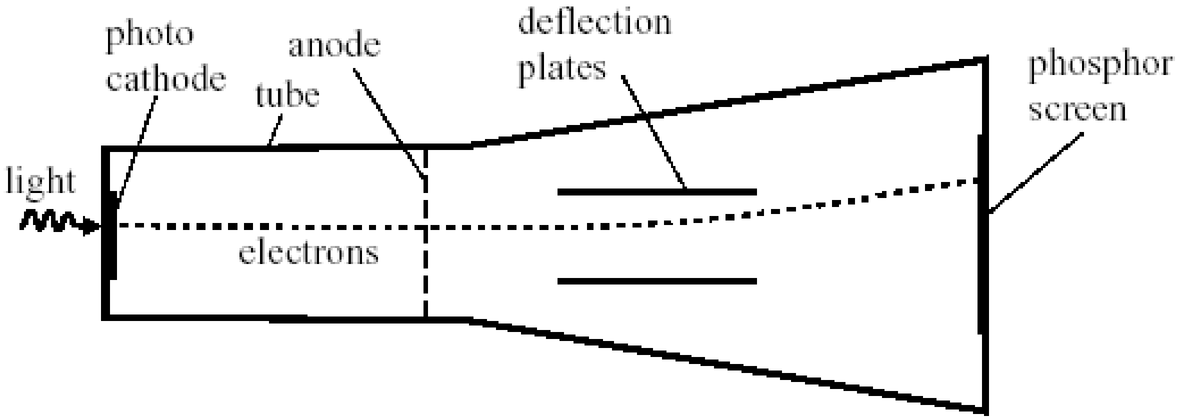


Ref: Per Ragnarsson PhD thesis

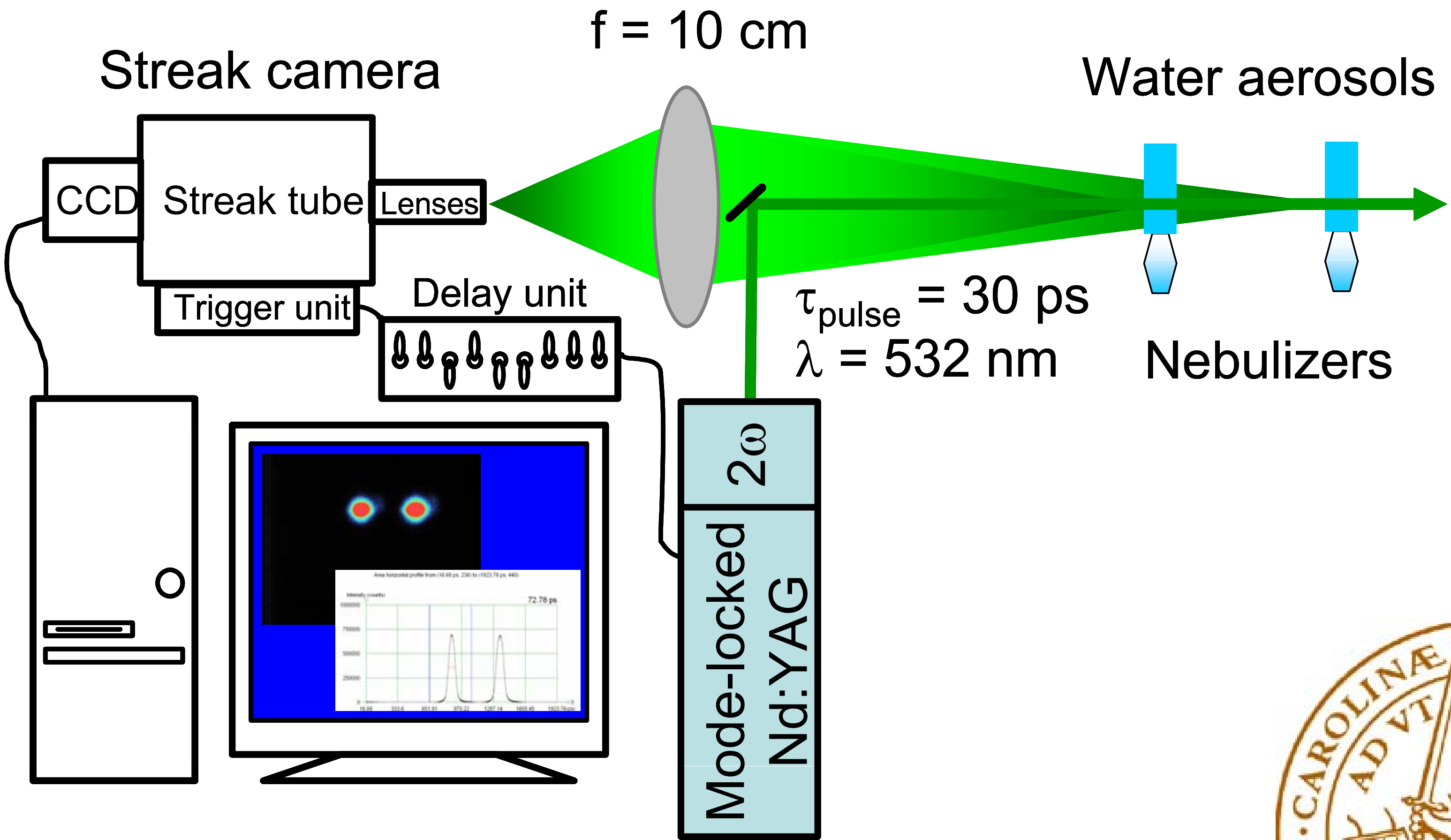
Conventional LIDAR – ps LIDAR

- Due to a laser pulse of ~10 ns the spatial resolution is ~ 1.5 m, far much higher than required.
- Using a ps laser (~10ps) the spatial resolution is a couple of mm.
- As detector an ultrafast response is also required; a streakcamera.

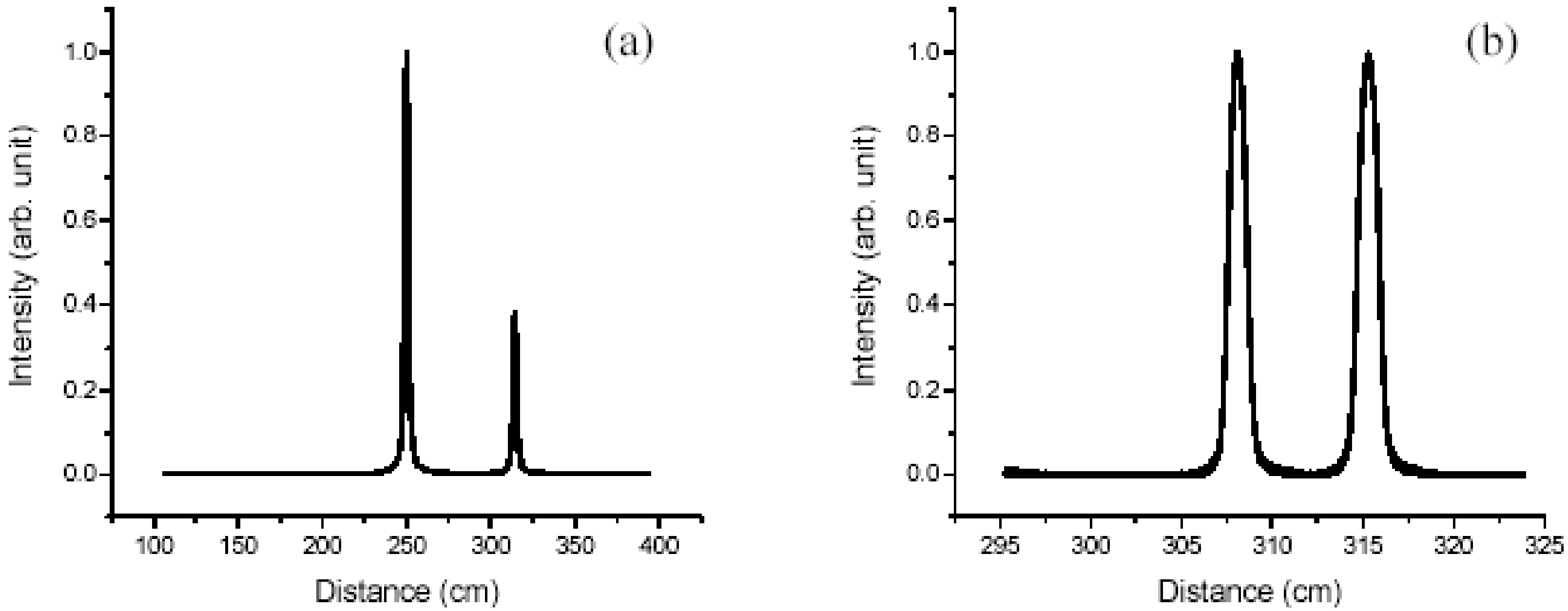
Streak camera



Experimental set-up for ps-lidar
(proof of principle)



Results



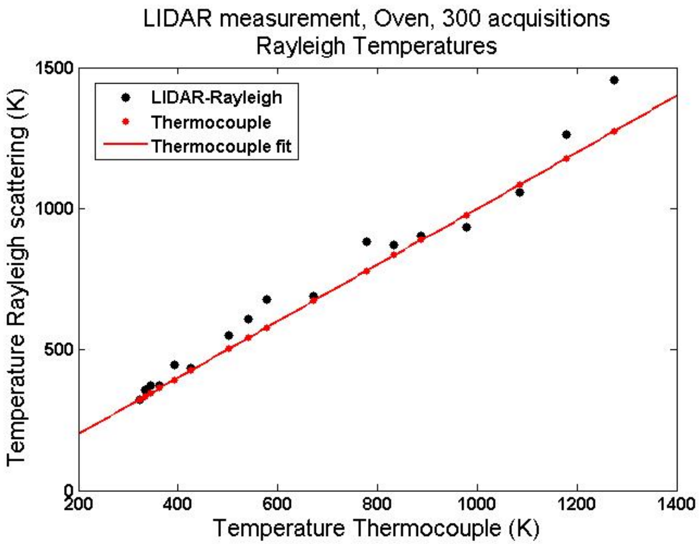
a) Nebulizers positioned 65 cm apart. The range resolution is in this case limited to 3 cm due to the slow streak rate (1 ns/mm) of the streak camera necessary to cover a total measurement range of 3 m.

b) Nebulizers localized 7 cm from each other, range resolution is 5 mm set by the pulse duration of the laser (30 ps).

Laboratory LIDAR feasability studies

Rayleigh scattering

1 D



Courtesy: Kaldvee and Bood 2010

2 D

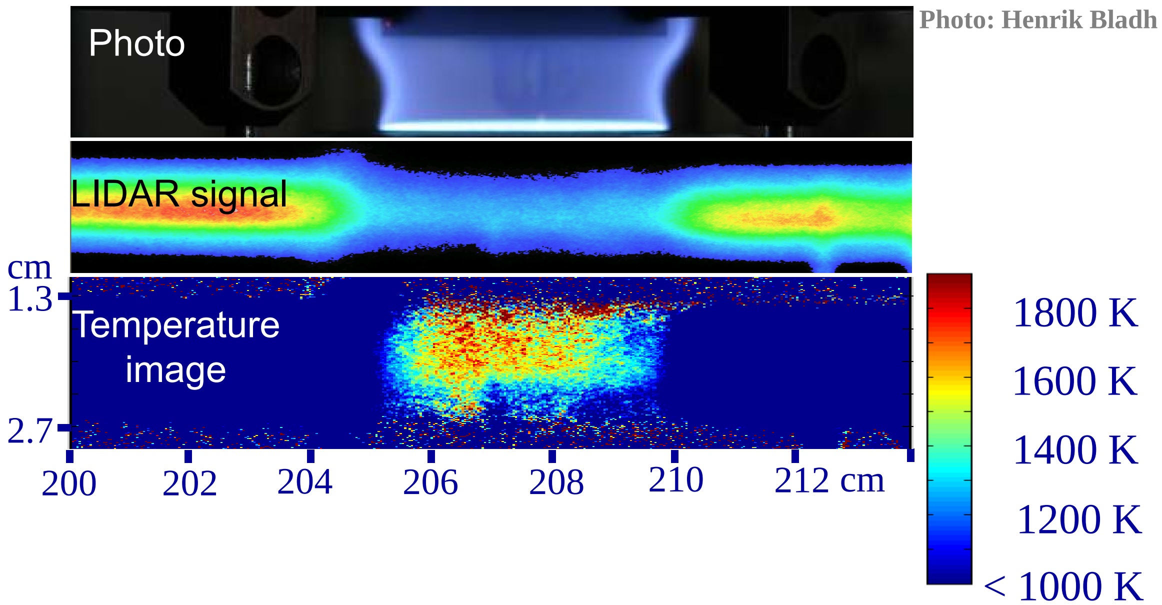
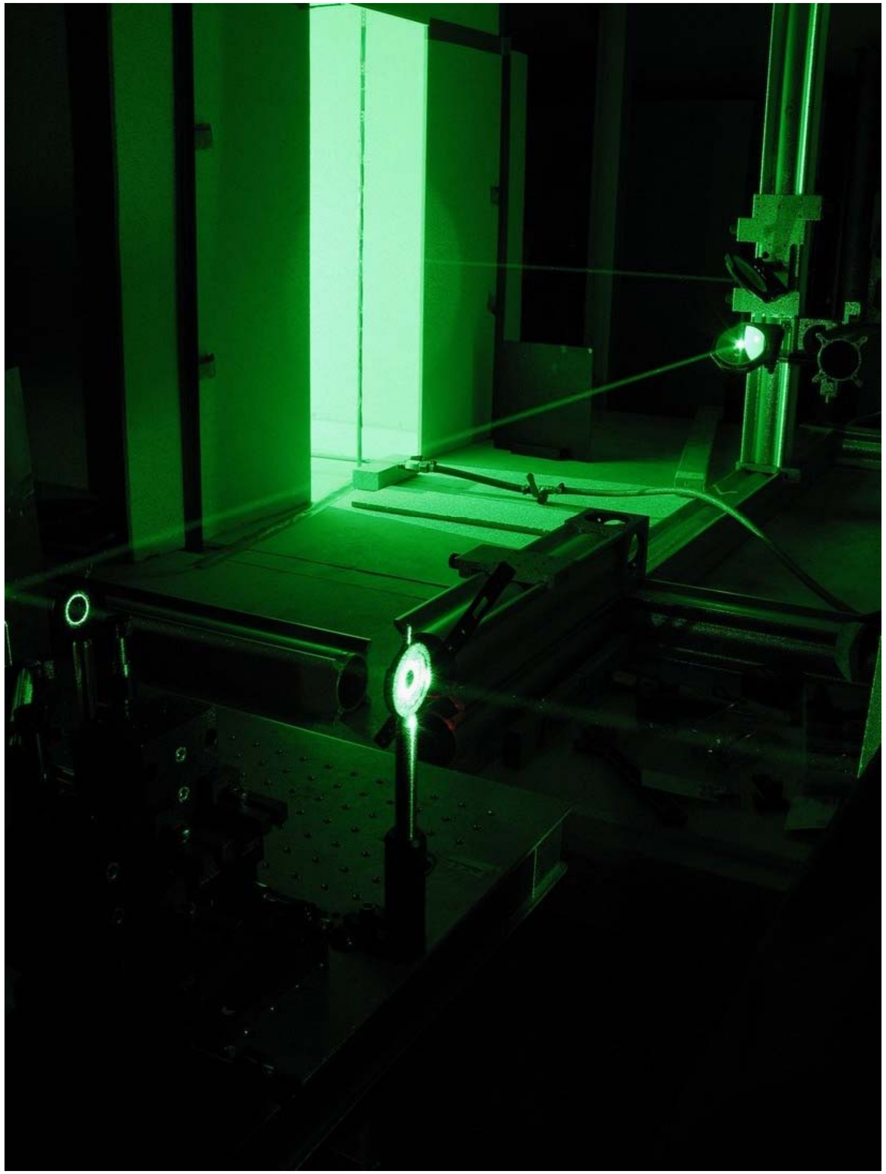


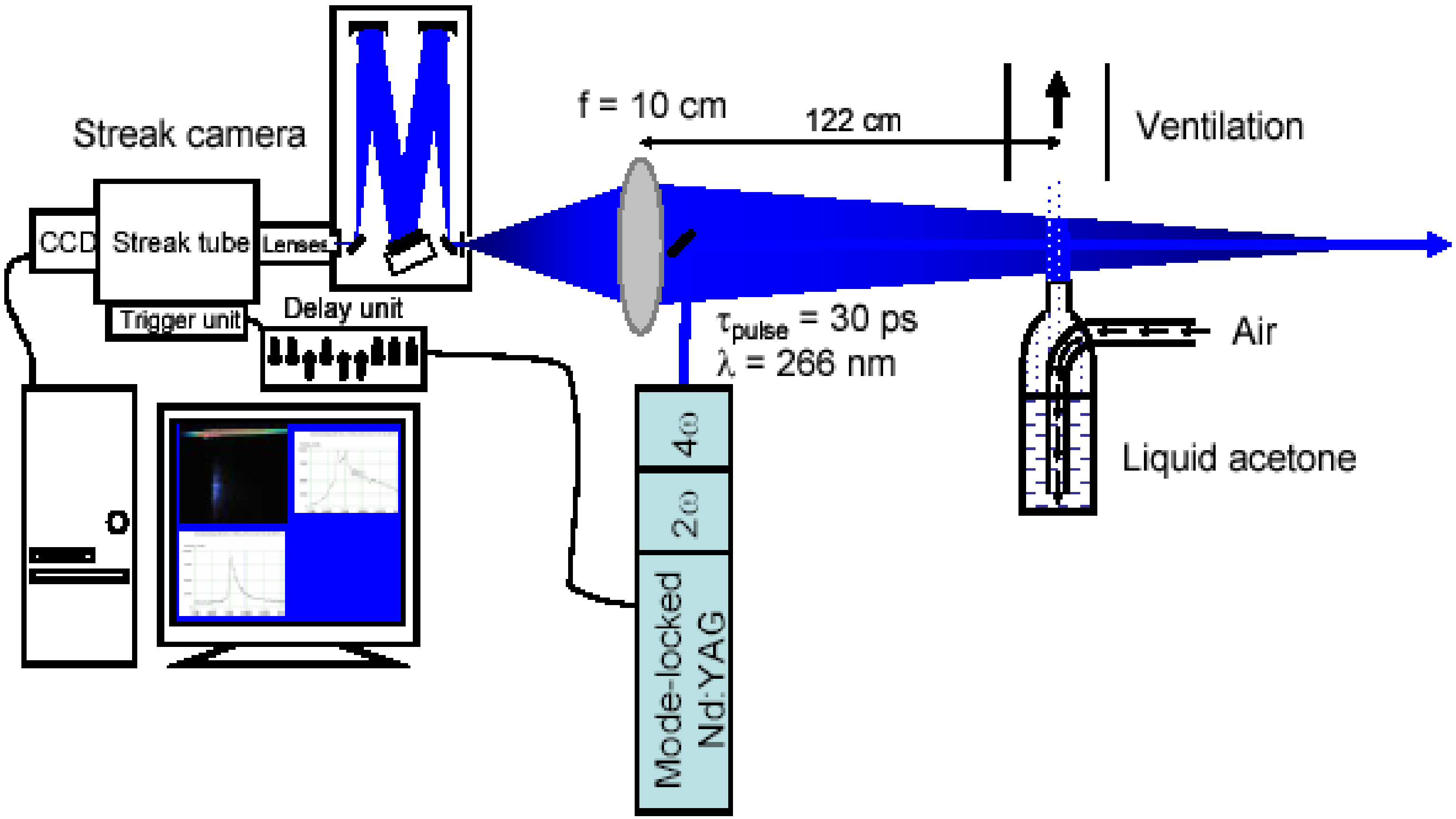
Photo: Henrik Bladh

Kaldvee et al. Appl. Opt 2009

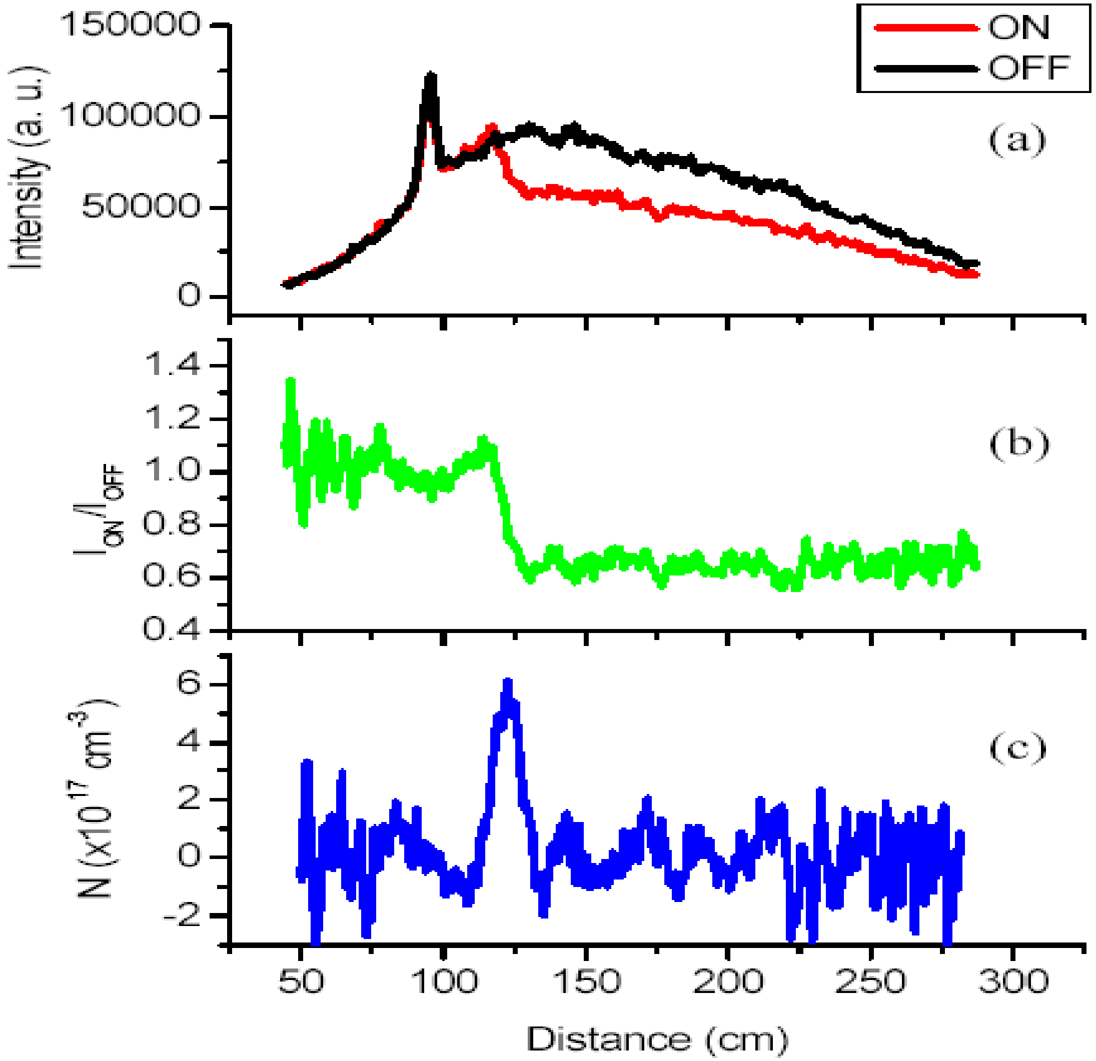
ps-LIDAR in a fire experiment



Experimental set-up ”DIAL”



DIAL results

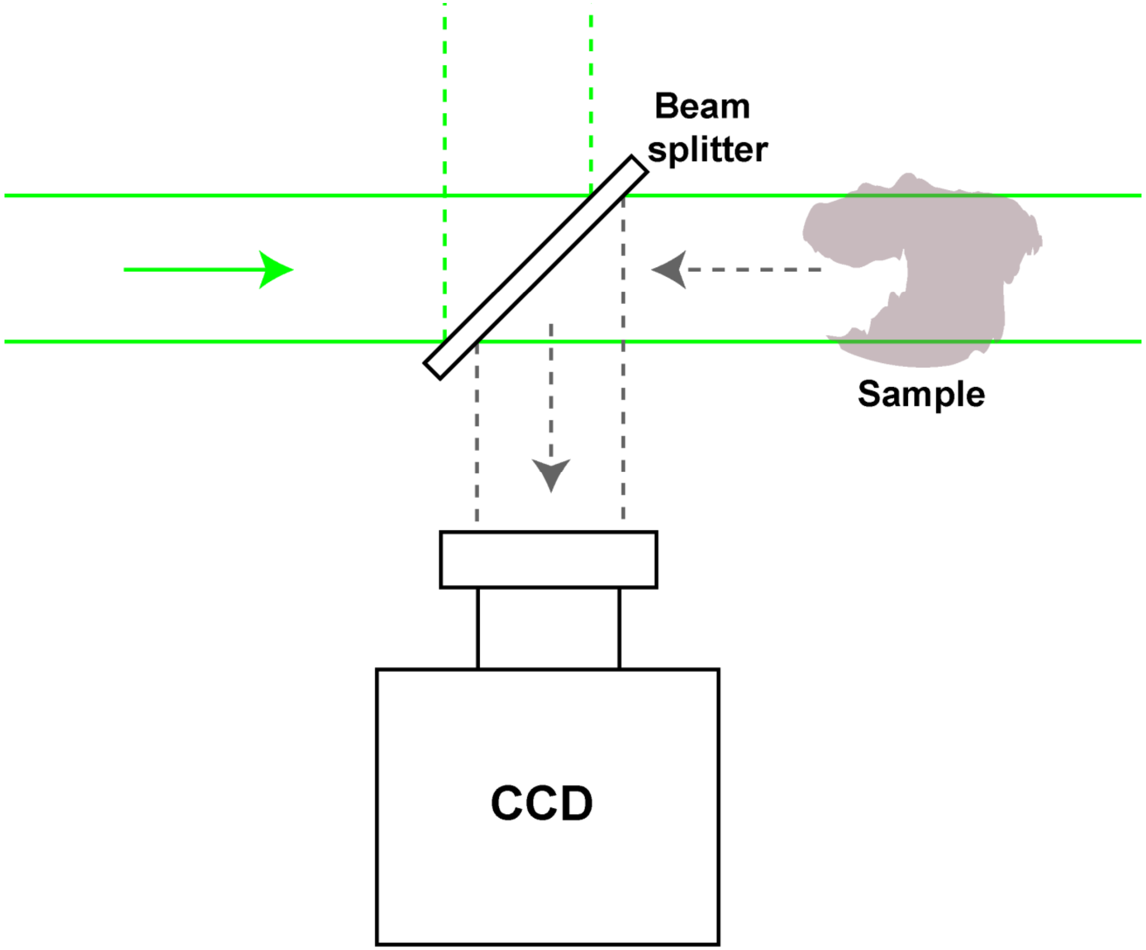


How can spatially resolved measurements be made in situations with very limited optical access?

Can a backscattered technique be developed for sub-cm resolution?

- **Potential approach: ps-LIDAR**
- **Potential approach: Structured illumination**

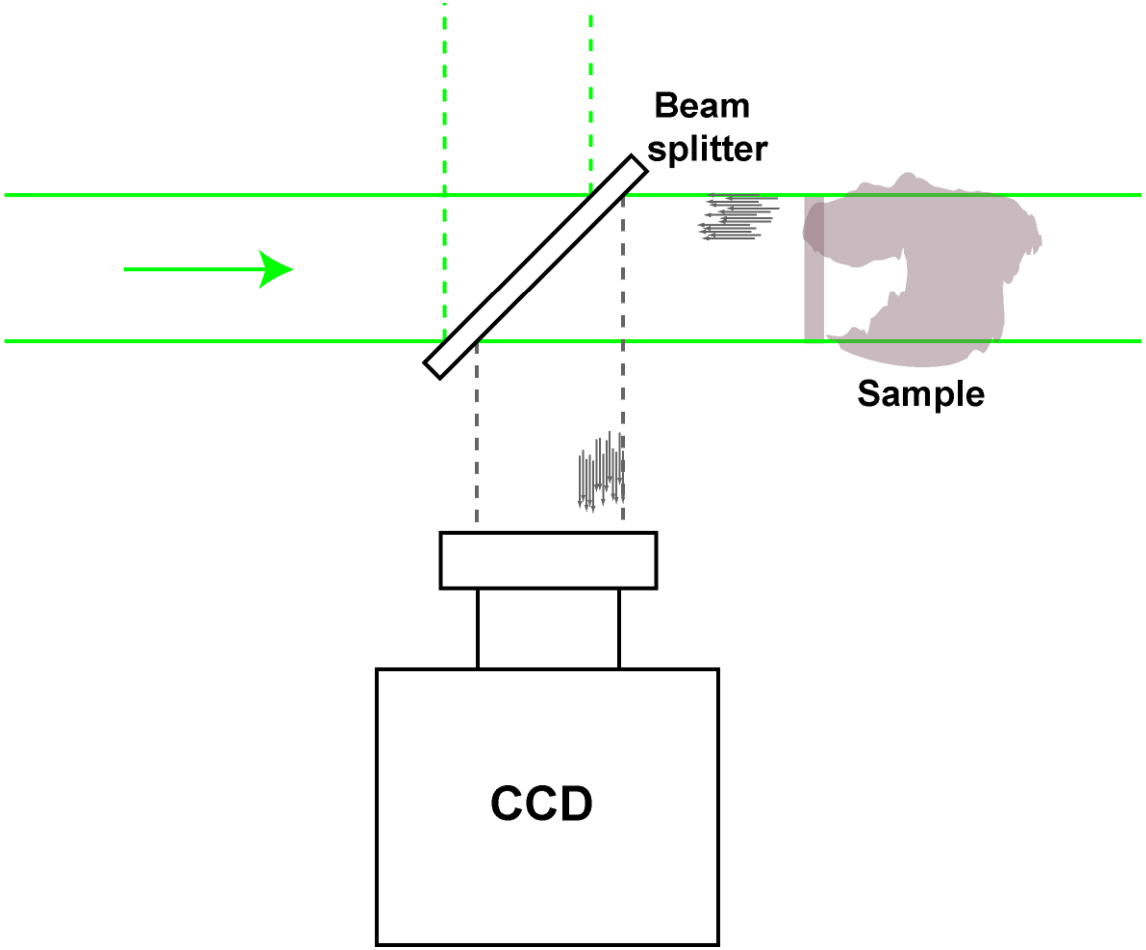
Conventional backscattering arrangement



Light that is back-scattered is collected from ALL sections of the sample.

NO depth-resolution possible.

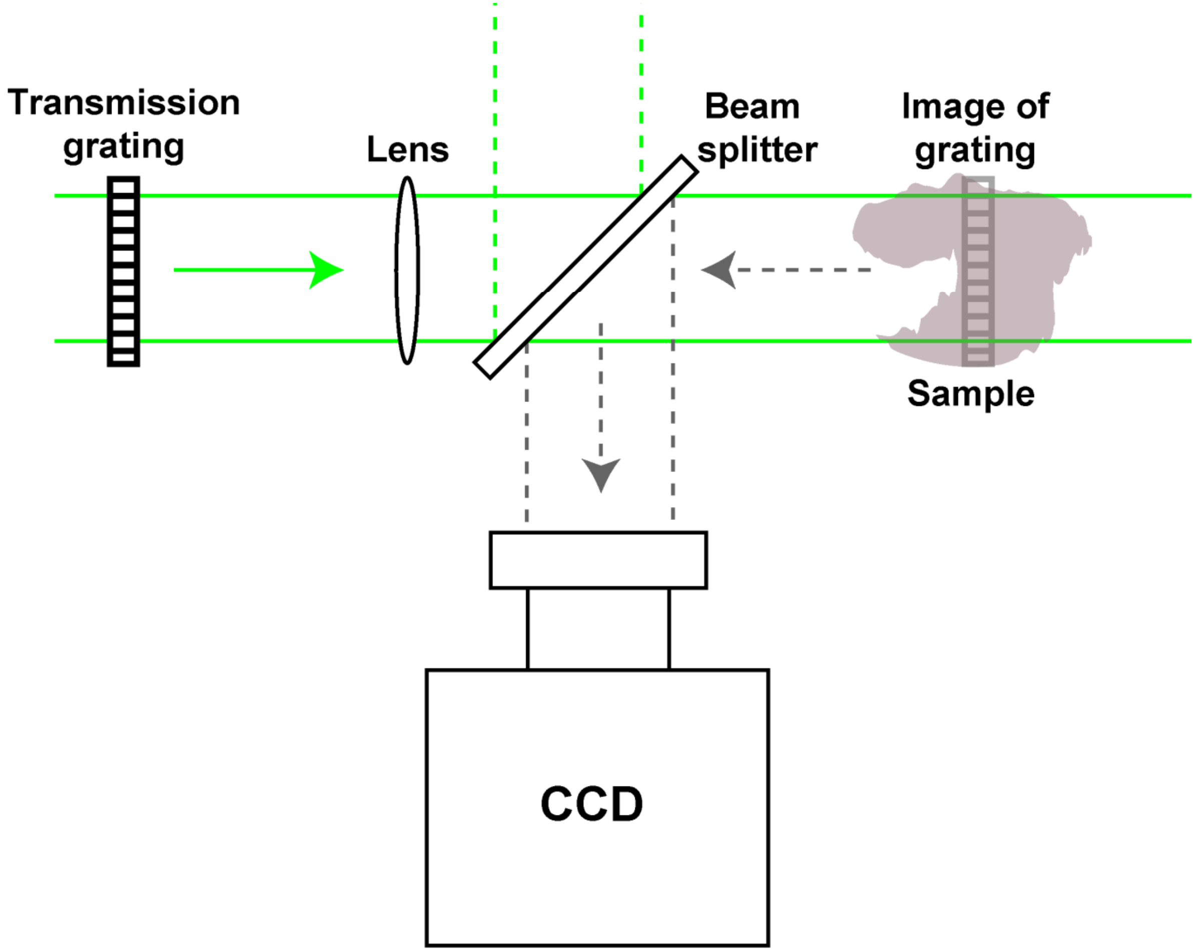
Conventional backscattering arrangement



Light that is back-scattered is collected from ALL sections of the sample.

NO depth-resolution possible.

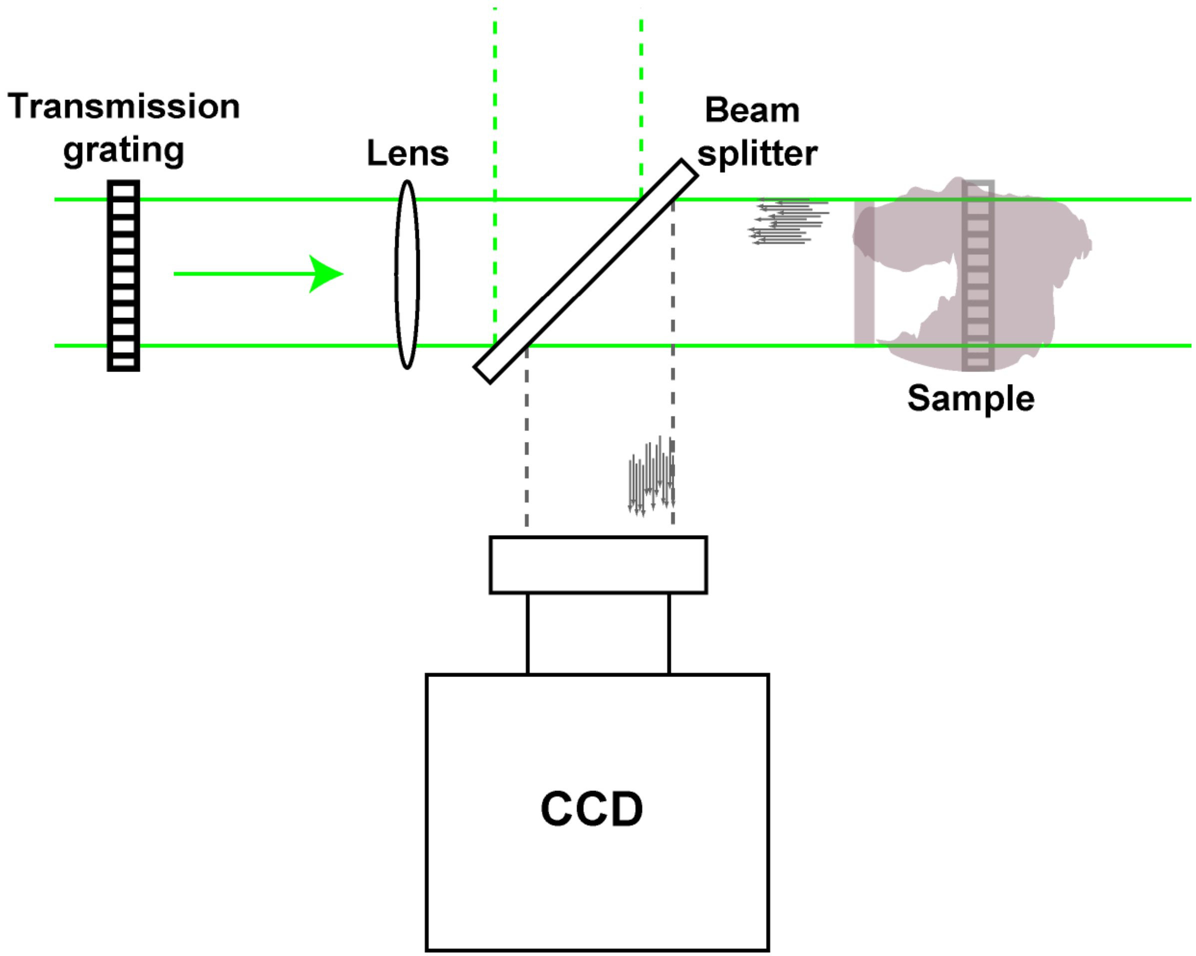
New backscattering arrangement



Light that is back-scattered is <u>STILL</u> collected from <u>ALL</u> sections of the sample.

Depth-resolution is <u>possible</u> as a section is different from the others.

New backscattering arrangement



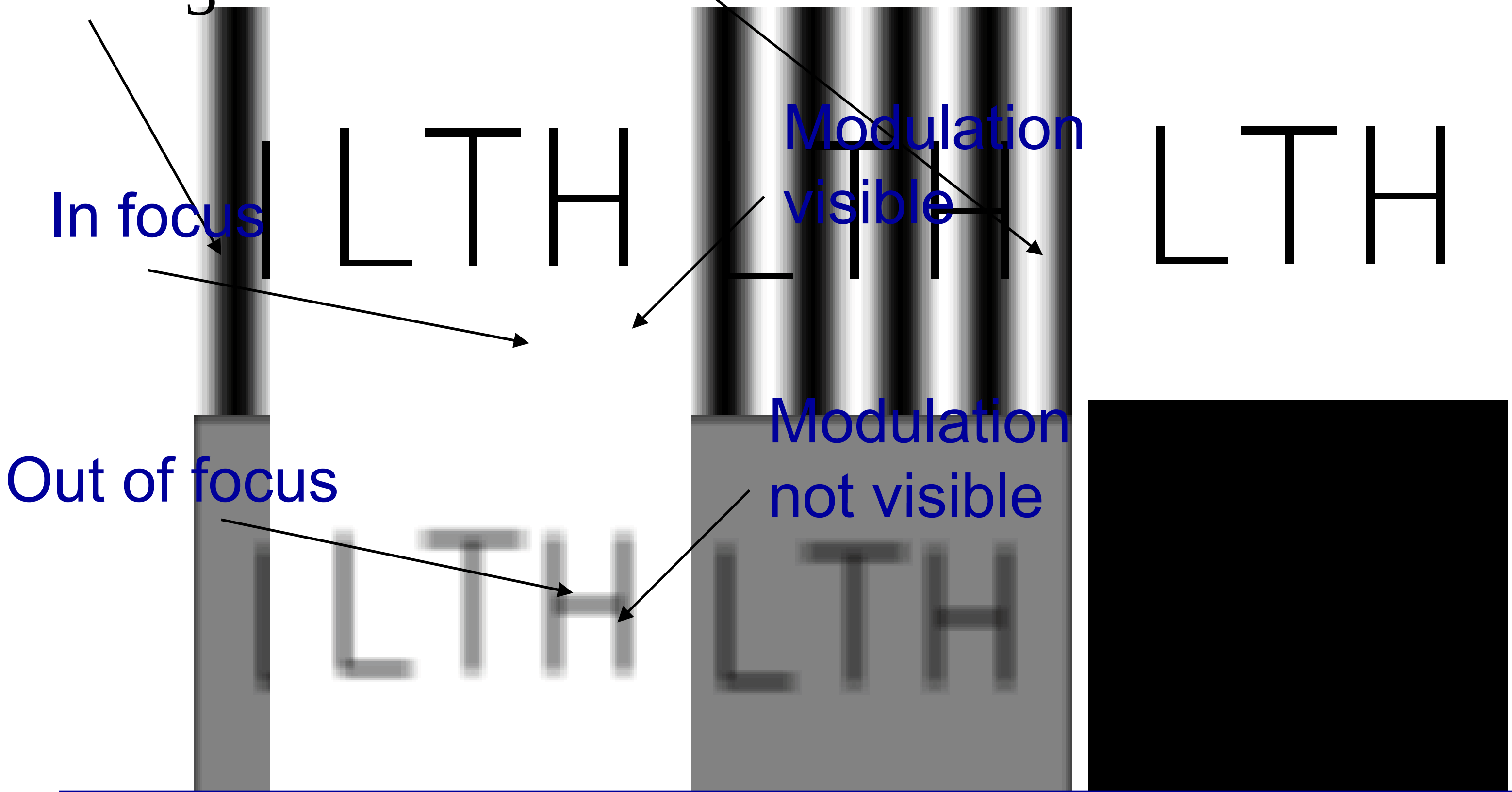
Light that is back-scattered is <u>STILL</u> collected from <u>ALL</u> sections of the sample.

Depth-resolution is <u>possible</u> as a section is different from the others.

Stuctured Illumination - Illustration

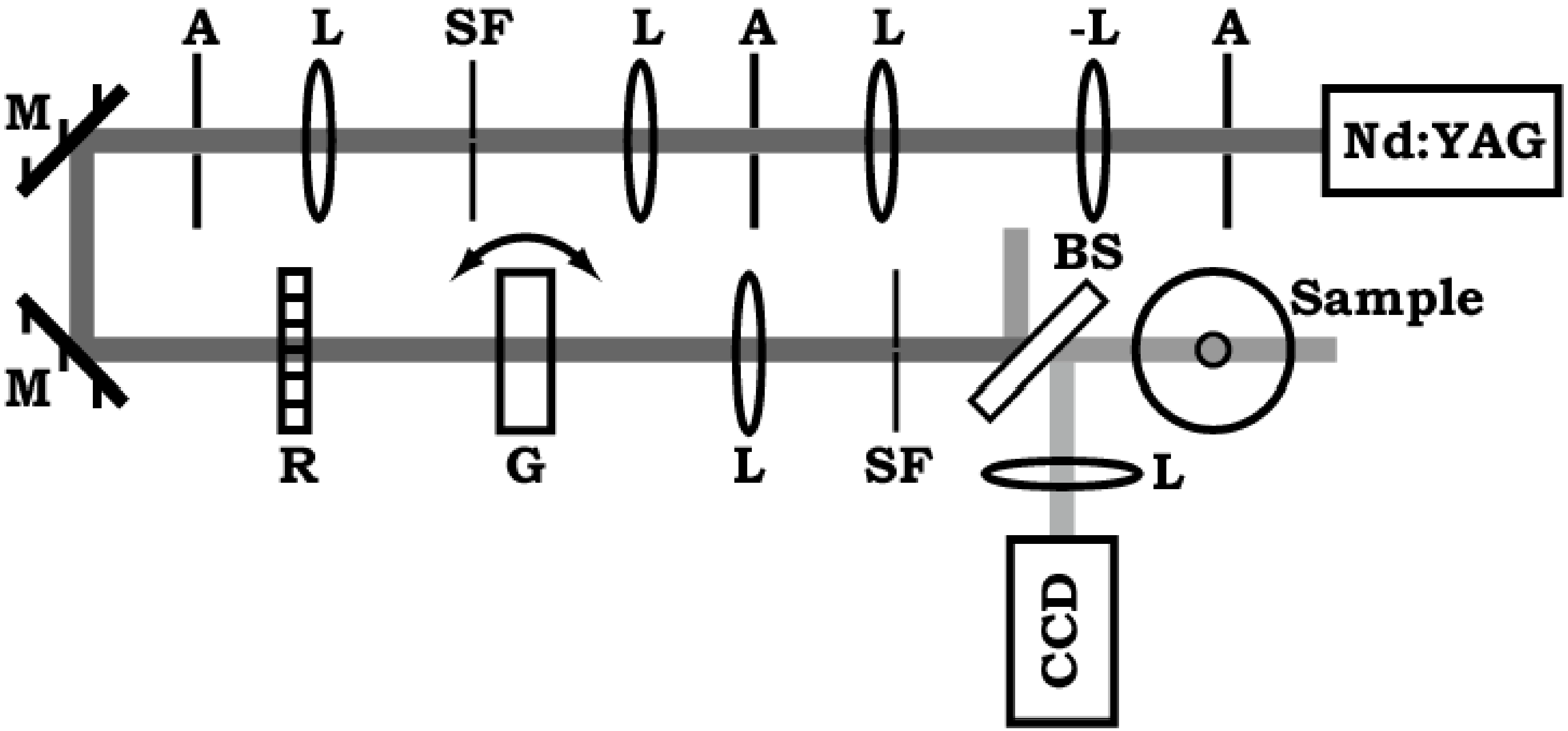
$$I_C = \frac{1}{3}\left(I_1 + I_2 + I_3\right)$$

$$I_S = \frac{\sqrt{2}}{3}\left[\left(I_1 - I_2\right)^2 + \left(I_1 - I_3\right)^2 + \left(I_2 - I_3\right)^2\right]^{1/2}$$



The difference between ”normal” imaging and structured illumination. In the image to the left, the lower plane is still visible, while it is removed in the image to the right.

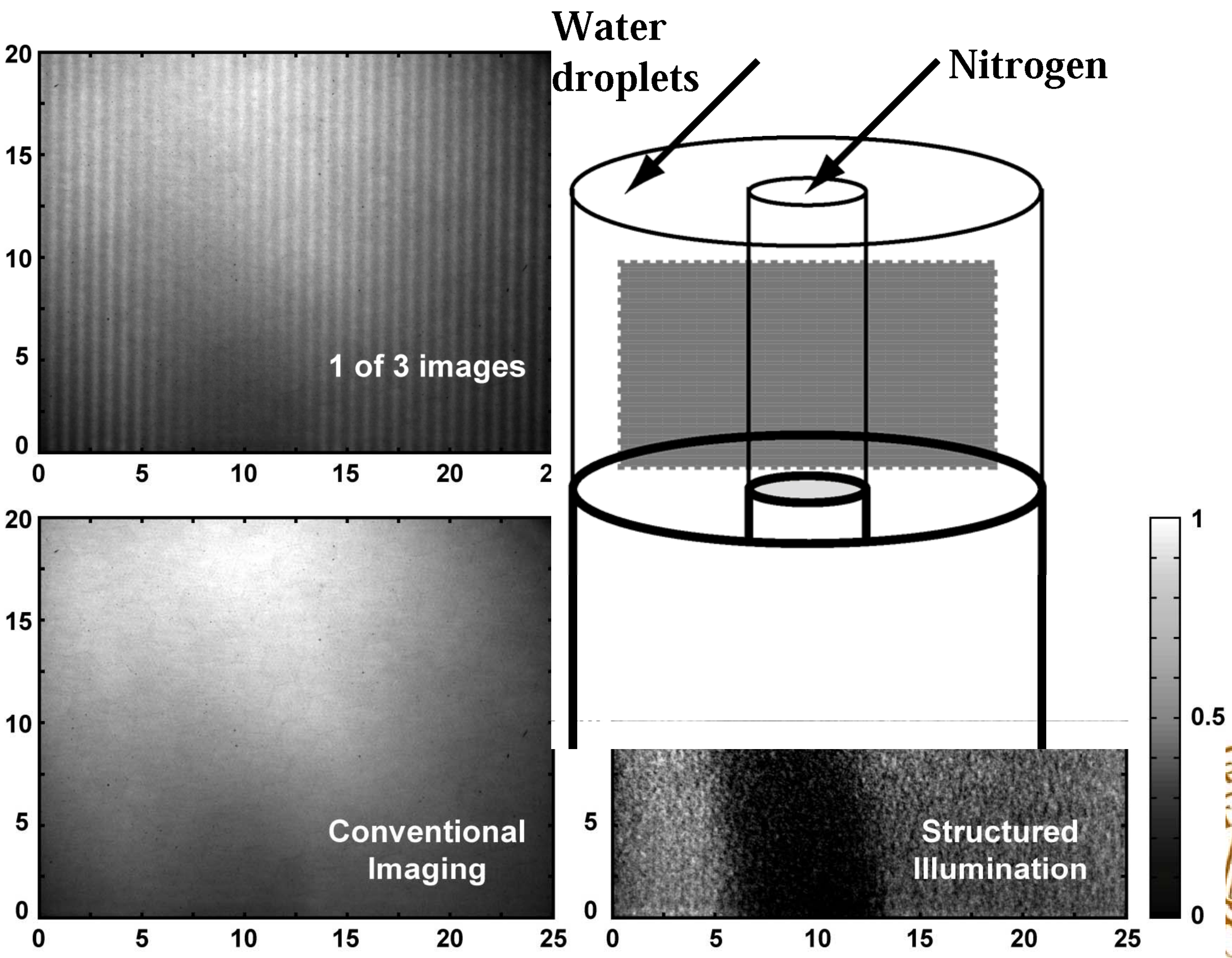
Experimental Setup



A = aperture, L = lens, SF = spatial filter, M = mirror, R = Ronchi ruling, G = glass plate, BS = beam splitter

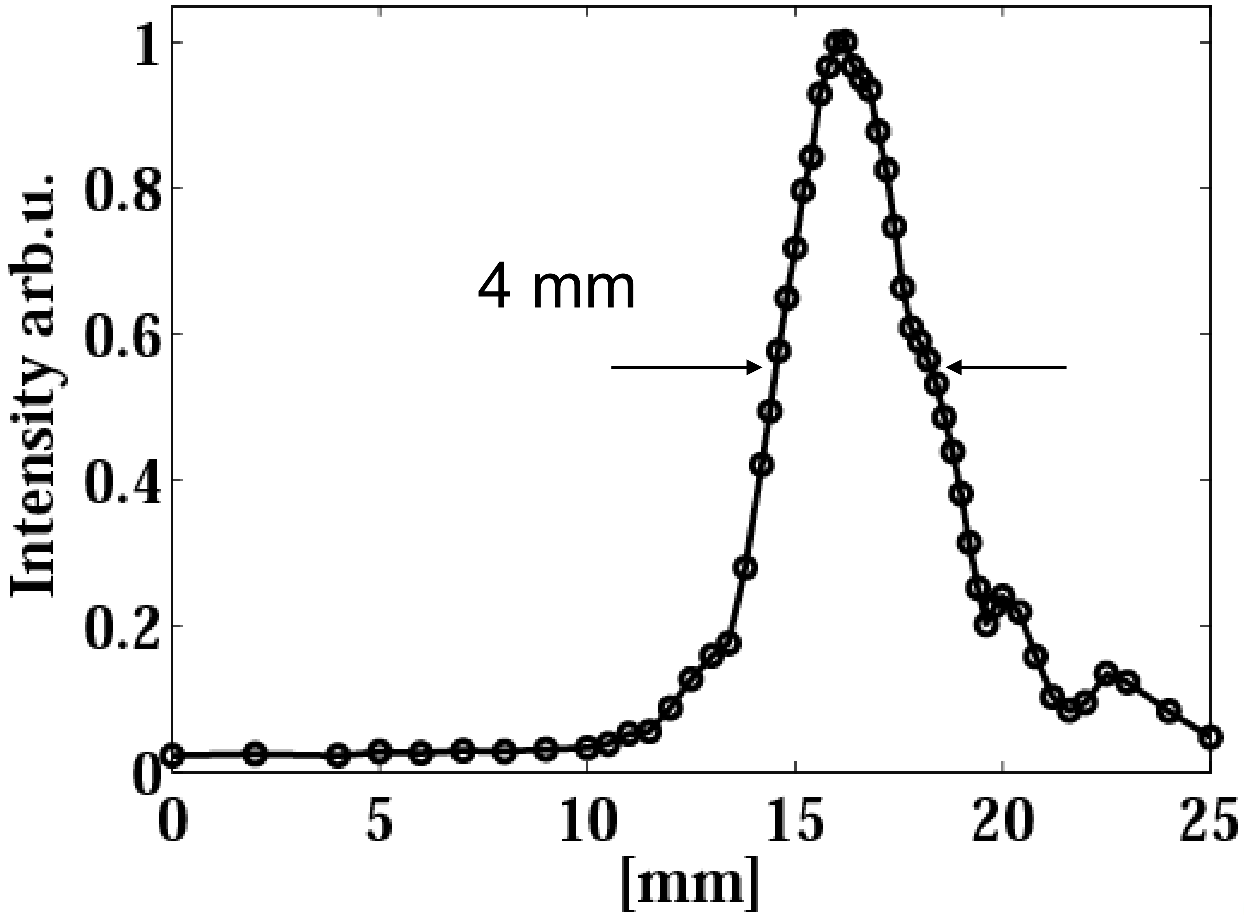
Kristensson et al. Appl. Opt . 2008 .

Results



Kristensson et al. Appl. Opt . 2008 .

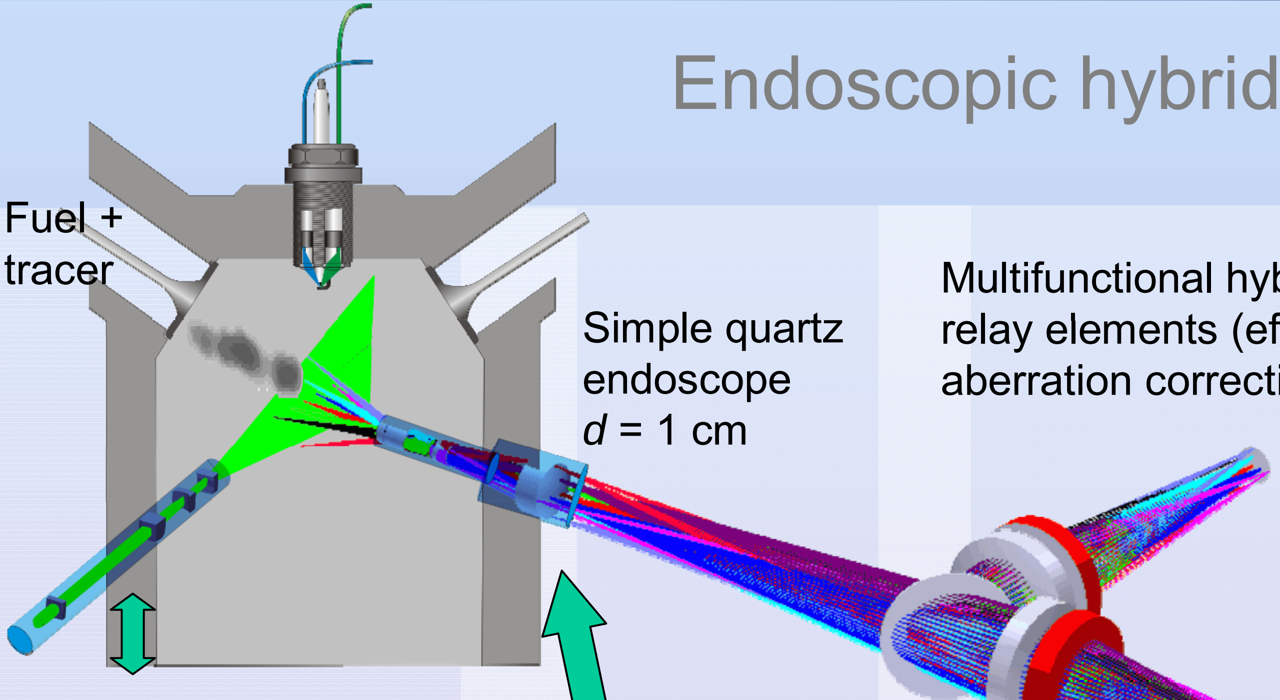
Depth-resolution



Depth-resolution approximately 4 mm

Limited optical access: Engines, gasturbines

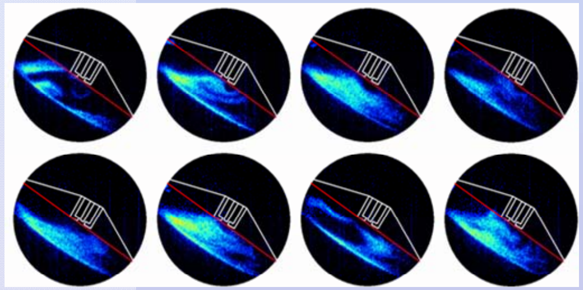
Endoscopic hybrid imaging system



Fuel + tracer

Simple quartz endoscope
d = 1 cm

Multifunctional hybrid relay elements (effective aberration correction)

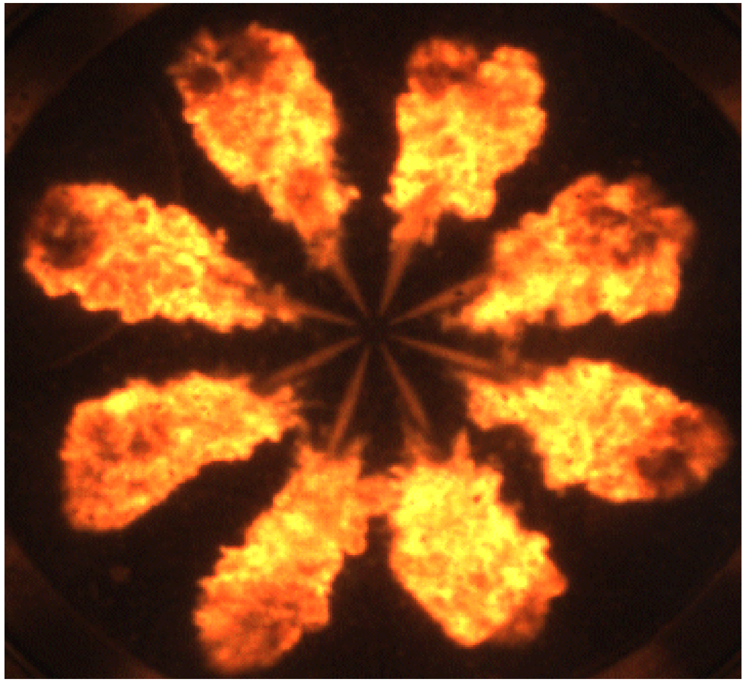


Beam-shaping endoscope (266 nm)
d = 9 mm

Courtesy C. Schultz (C. Gessenhardt, F. Zimmermann, C. Schultz, R. Reichle, C. Pruss and W. Osten, *Hybrid endoscopes for laser based imaging diagnostics in IC engines*, SAE 2009-01-0655)

Challenges in optical dense medium

- **Extinction**
- **Multiple scattering**



Possible techniques:

Ballistic imaging (Linne et al. Proc. 32 Comb. Symp.)

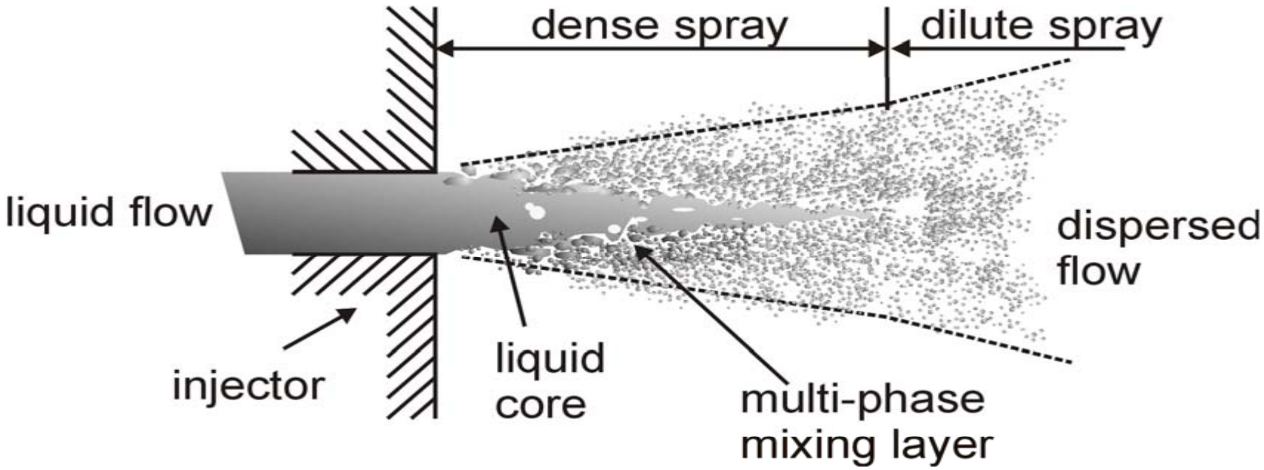
X-ray scattering (Wang et al. Nat. Phys. (2008)

Structured laser illumination planar imaging, SLIPI

Motivation

- To burn liquid fuels at an effective rate, the liquid must be rapidly dispersed into the air using a spray
- Mixture preparation in an engine has a big effect on flame propagation, extinction, and emissions formation
- Sprays are complex flow fields that behave quite differently in different flow regimes:
  - steady or transient spray
  - ratio of fuel density to gas density
  - fuel vapor pressure
  - injector pressure drop
  - fuel stream Reynolds number
  - fuel surface tension and viscosity
  - internal architecture of the injector

Spray fluid-mechanical zones

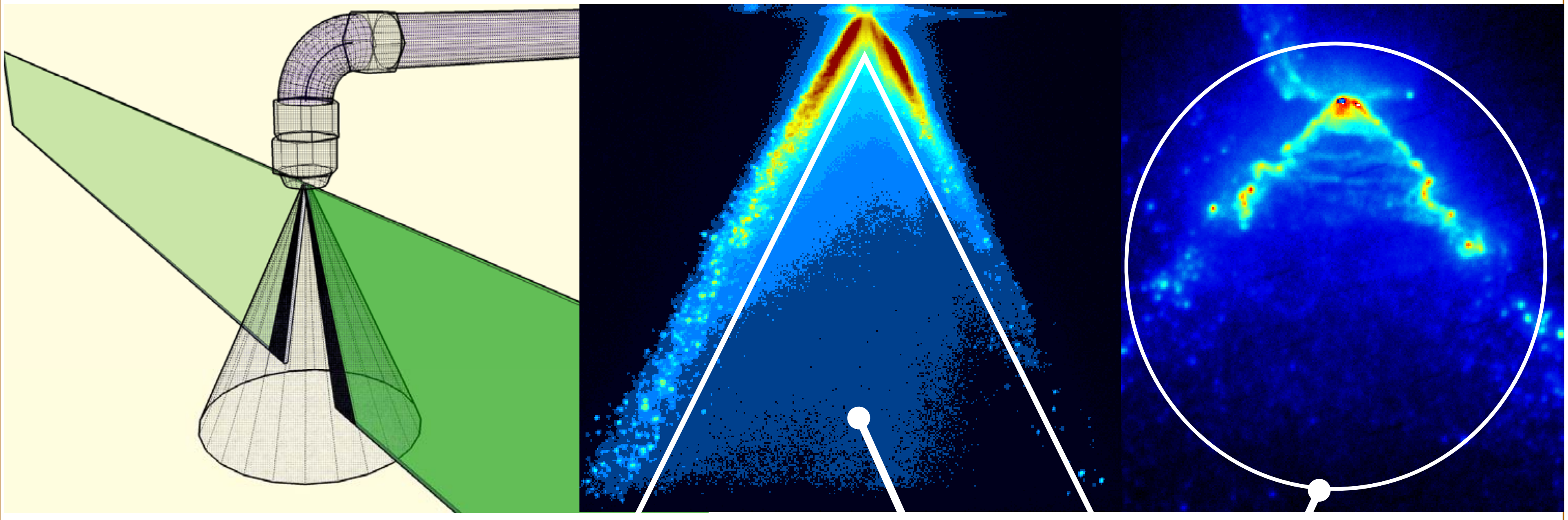


- a liquid core that intrudes into the gas phase
- a primary breakup region where the liquid core breaks into large droplets
- a secondary breakup region where primary droplets break into smaller droplets
- a vaporization region where the small droplets are evaporated prior to burning

Measurements in optically dense environment:

- **SLIPI**
- **Ballistic imaging**

Examples of planar laser images



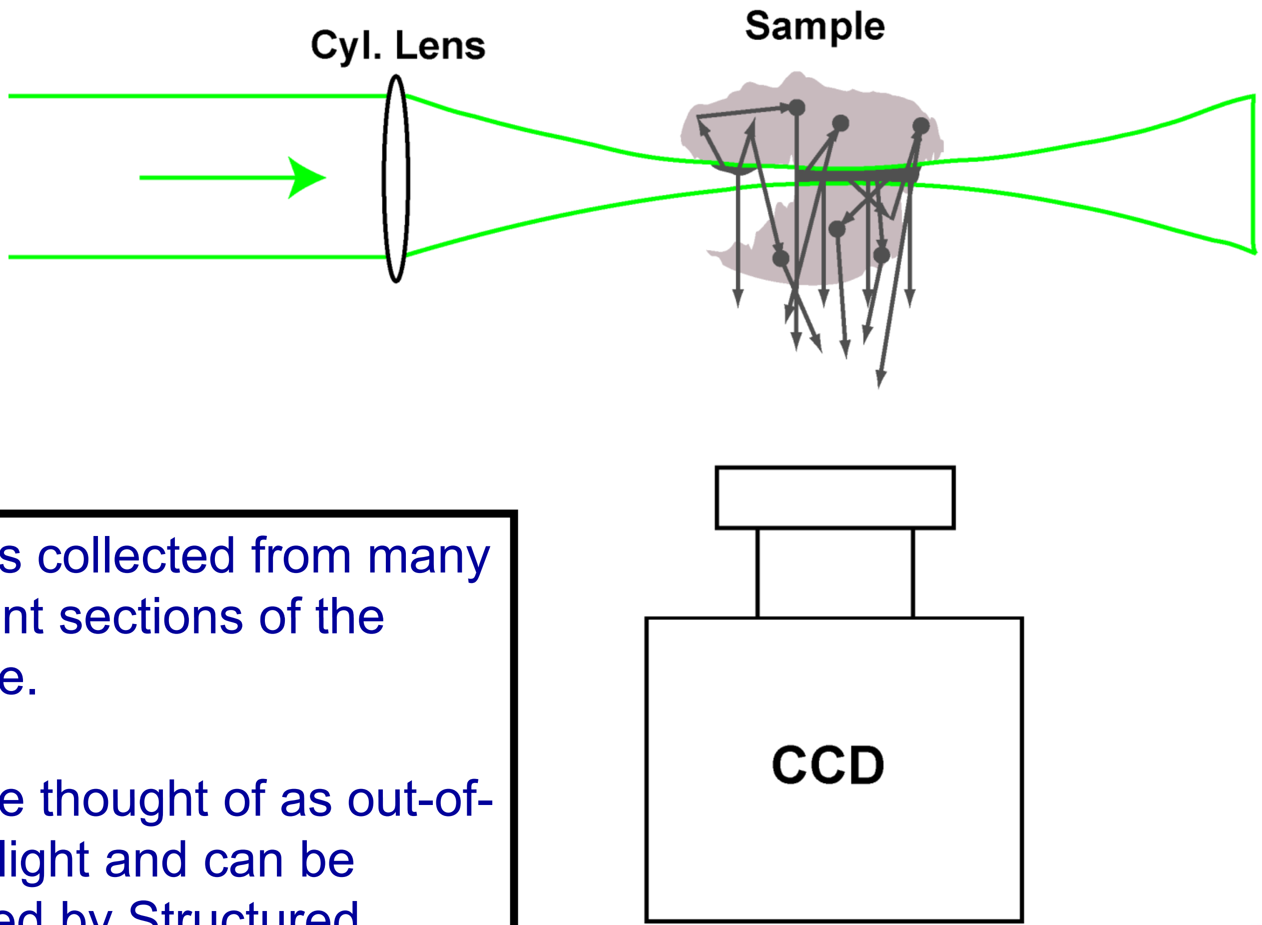
Wrong light intensity contribution

Aureole of light blurring the image

Planar Laser Imaging is principally restricted by errors introduced by Multiple Scattering, especially in the Dense Spray Region

Courtesy: Elias Kristensson, Edouard Berrocal

Scattering from a dense medium

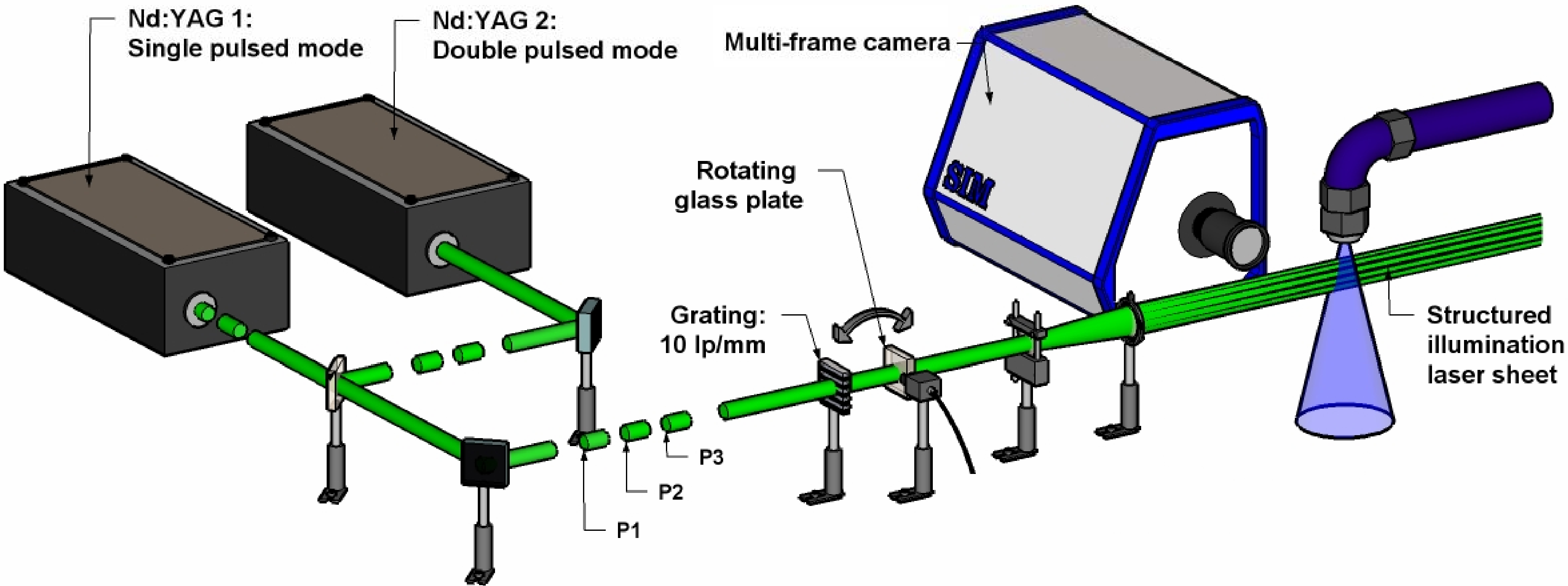


Light is collected from many different sections of the sample.

Can be thought of as out-of-focus light and can be reduced by Structured Illumination!.

Courtesy: Elias Kristensson

Experimental set-up

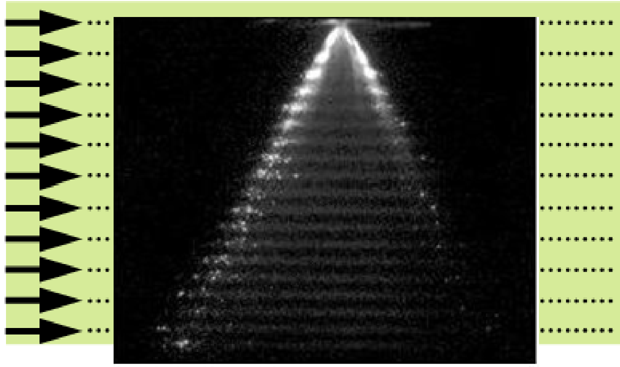


- **Water spray**
- **Pressure-swirl nozzle**
- **Type: *Danfoss* 1910**
- **Injection pressure: 50 bars**
- **50 averaged images**
- **12-bit intensified CCDs**

Kristensson et al. Opt Lett. 2008

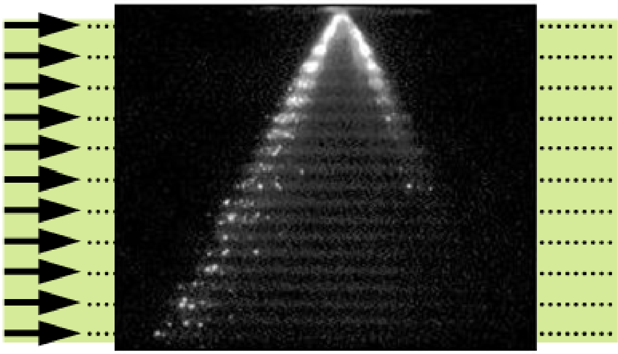
Structured Laser Illumination Planar Imaging - SLIPI

$\Phi = 0°$



I_1

$\Phi = 120°$



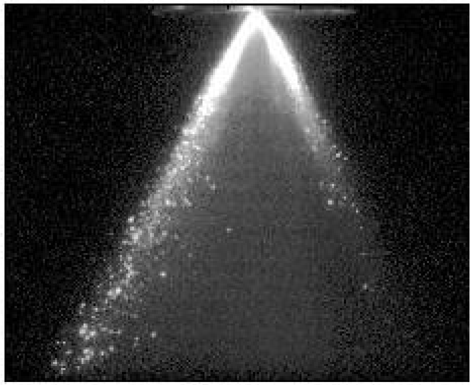
I_2

$\Phi = 240°$

I_3

$$I_C = \frac{I_1 + I_2 + I_3}{3}$$

$$I_S = \frac{\sqrt{2}}{3} \cdot \left[(I_1 - I_2)^2 + (I_1 - I_3)^2 + (I_2 - I_3)^2 \right]^{1/2}$$



Conventional

The SLIPI technique

Berrocal et al. Opt Express. 2008

Kristensson et al. Opt Lett. 2008

Measurements in optically dense environment:

- SLIPI
- Ballistic imaging

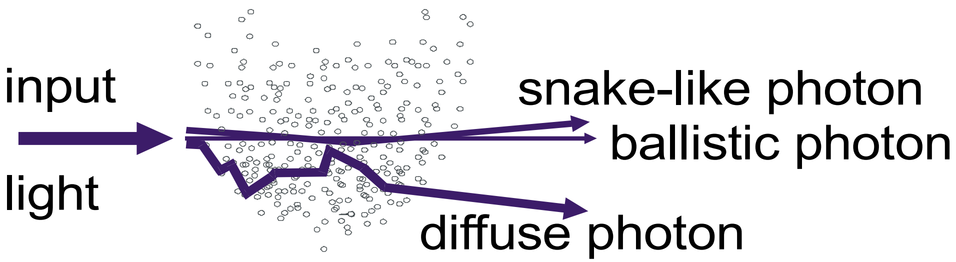
A diesel spray in the atomization regime

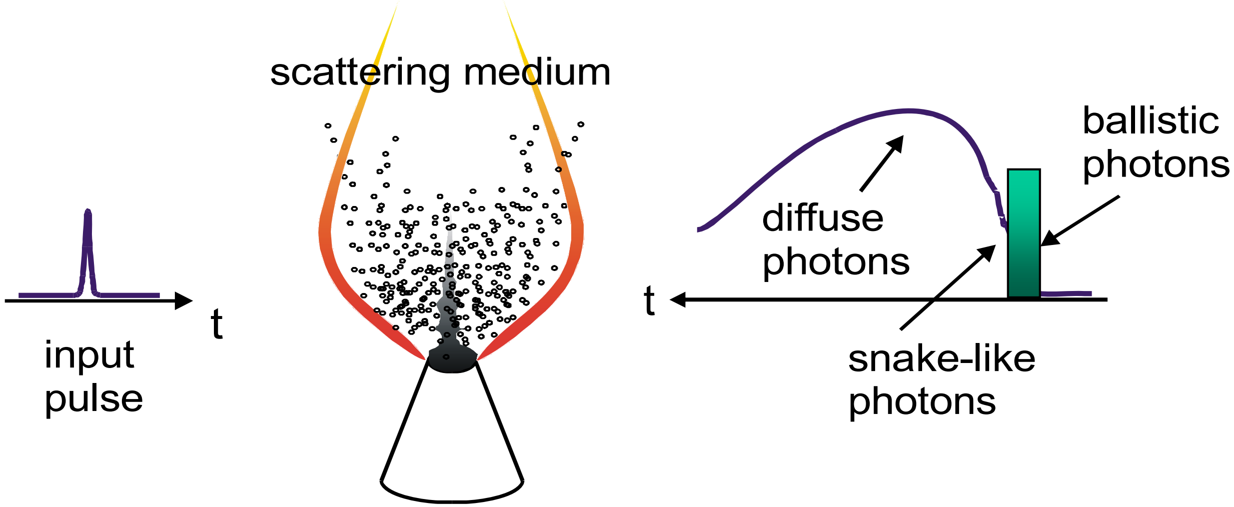
- Need direct experimental evidence regarding breakup of the liquid core at the exit of a spray
- The centerline of the near field (within 10 orifice diameters) is so dense that most optical beams are lost
- Light is highly attenuated in turbid media:

$$\frac{I}{I_o} = e^{-\mu_{ext} L} \text{, where } \quad \mu_{ext} \equiv N(\sigma_{abs} + \sigma_{scatt})$$

  - Diesel jets have an optical depth in the range $\mu_{ext} L$ ~ 5 - 15 (one measurement gives $\mu_{ext} L$ = 8), human tissue has $\mu_{ext} L$ = 11
- Need a high-resolution, single-shot imaging system for the liquid core <u>despite</u> the turbidity of the spray → ballistic imaging, a technique originally developed for medical imaging

Introduction to ballistic imaging

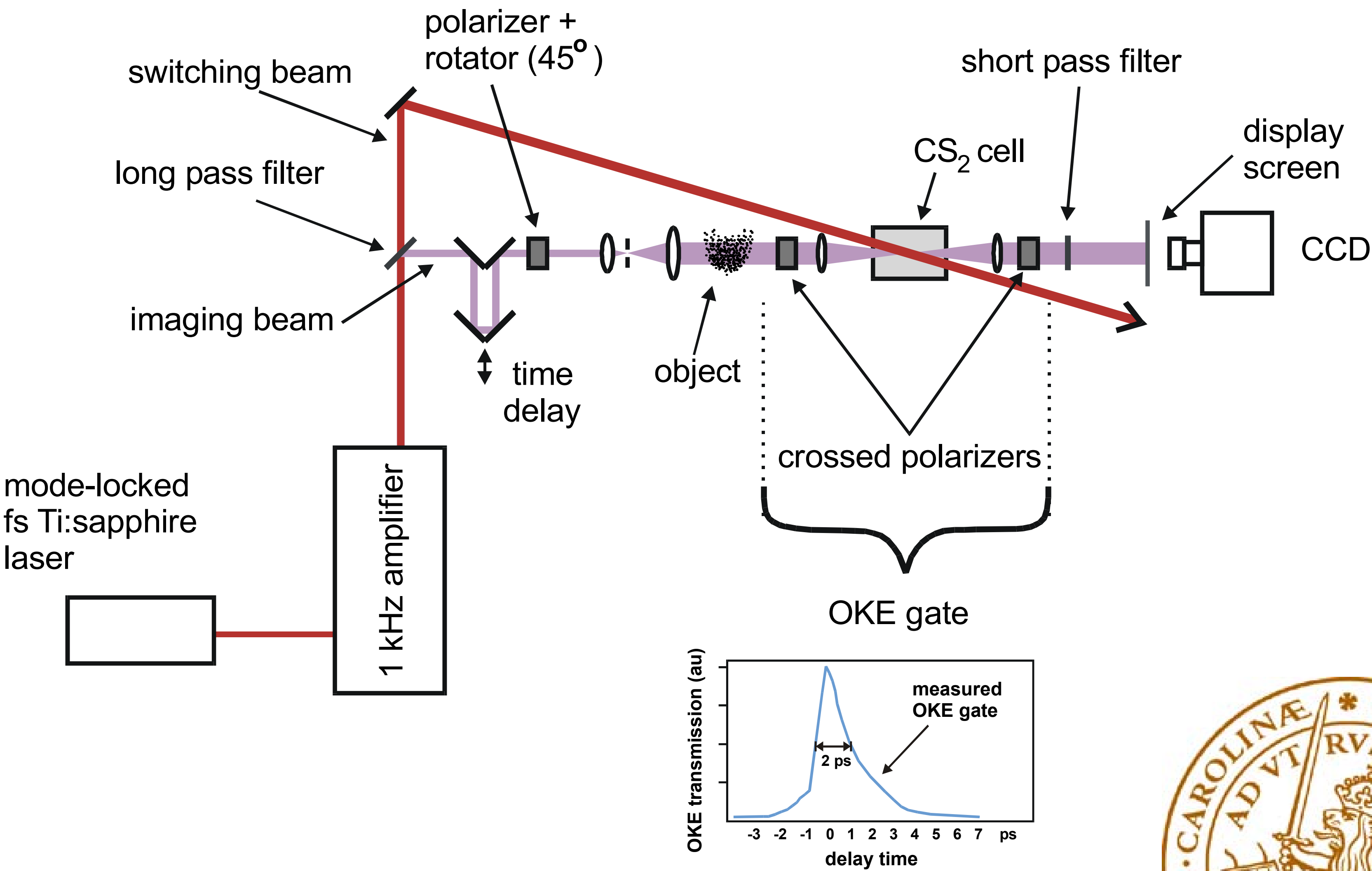




Even in dense media, some photons do not scatter, passing directly through the medium – called "ballistic photons"

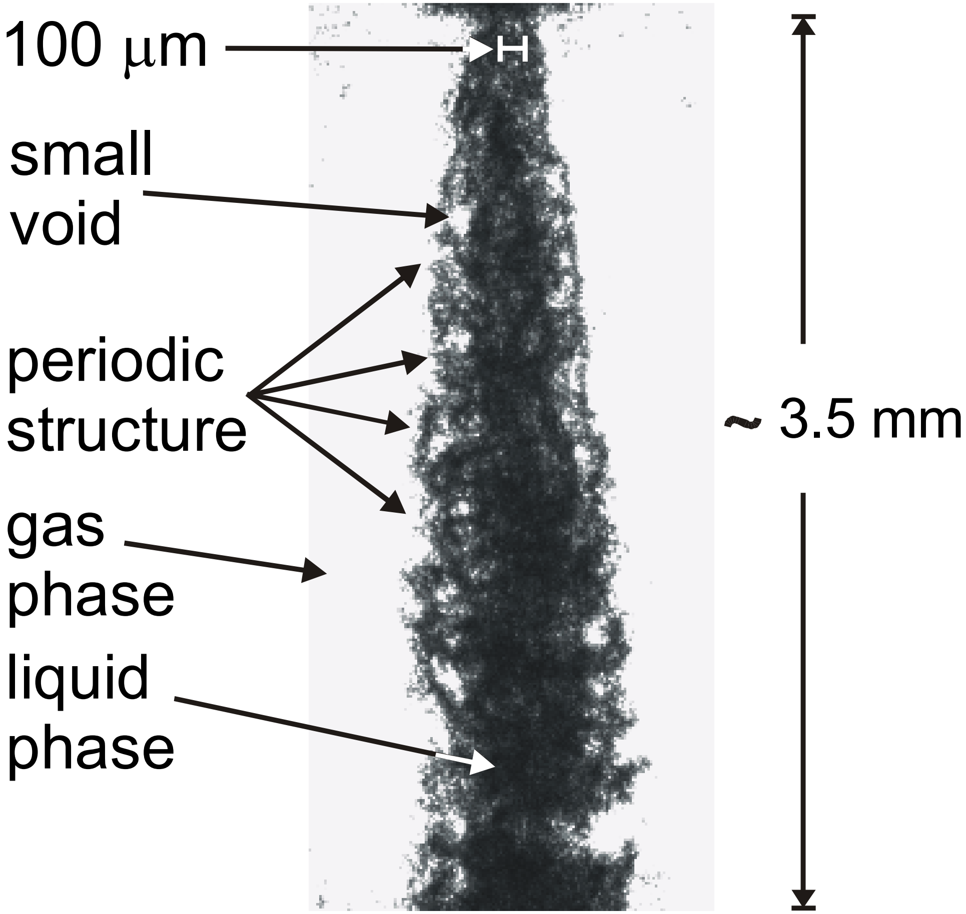
Because they do not scatter, ballistic photons have the shortest path length and exit first.

Transient time-gated ballistic imaging



Diesel spray result (1)

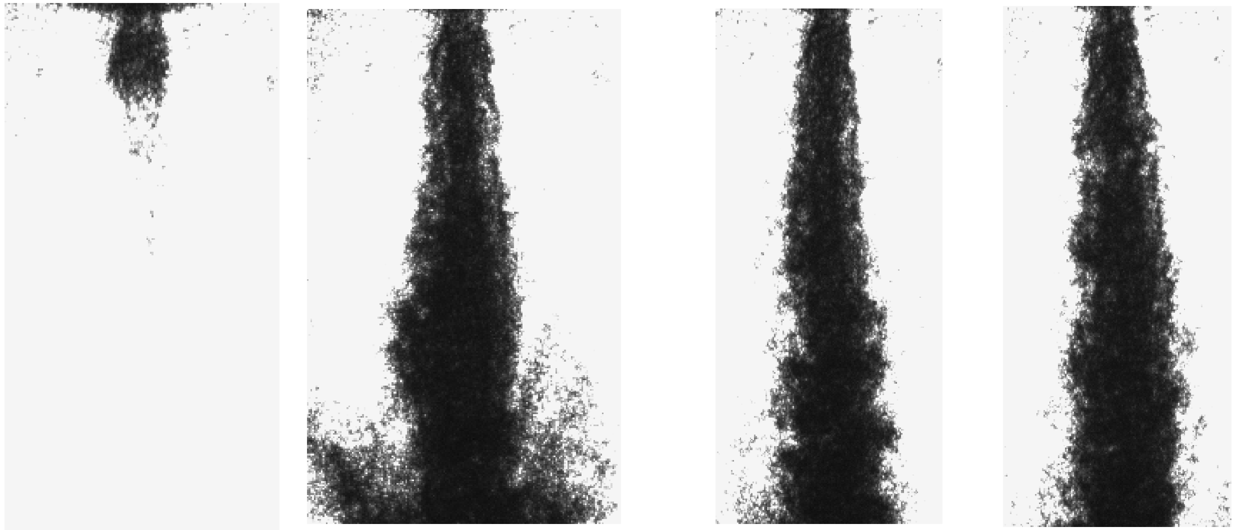
Example ballistic image during steady period



Diesel spray result (2)

Ballistic images of the spray developing over early times

(times are all given after the start of injection)



a. 2 µs b. 10 µs c. 94 µs d. 980 µs

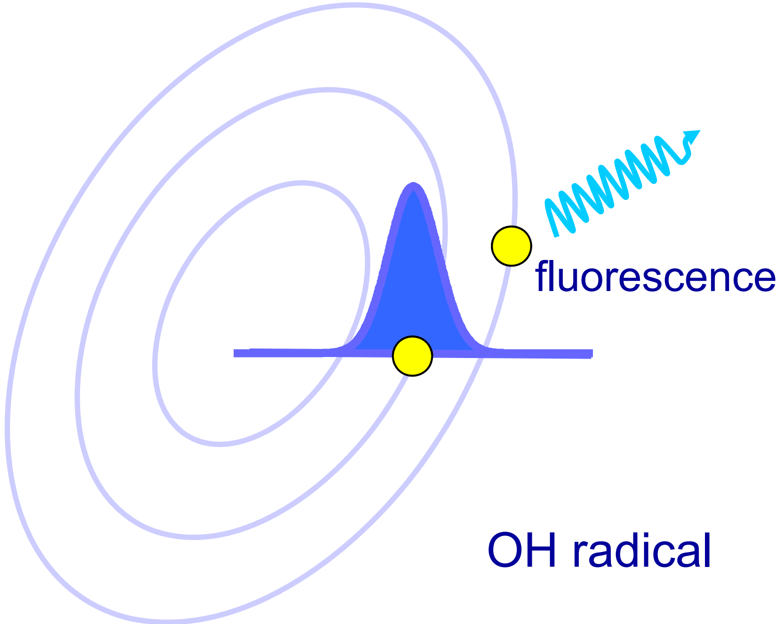
”New” species detection

Photofragmentation laser-induced fluorescence (PF-LIF)

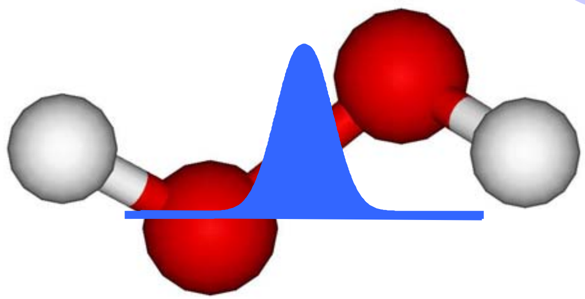
1. $H_2O_2 + h\nu \longrightarrow OH + OH$

2. $OH + h\nu \rightarrow OH^*$

3. $OH^* \rightarrow OH + h\nu$



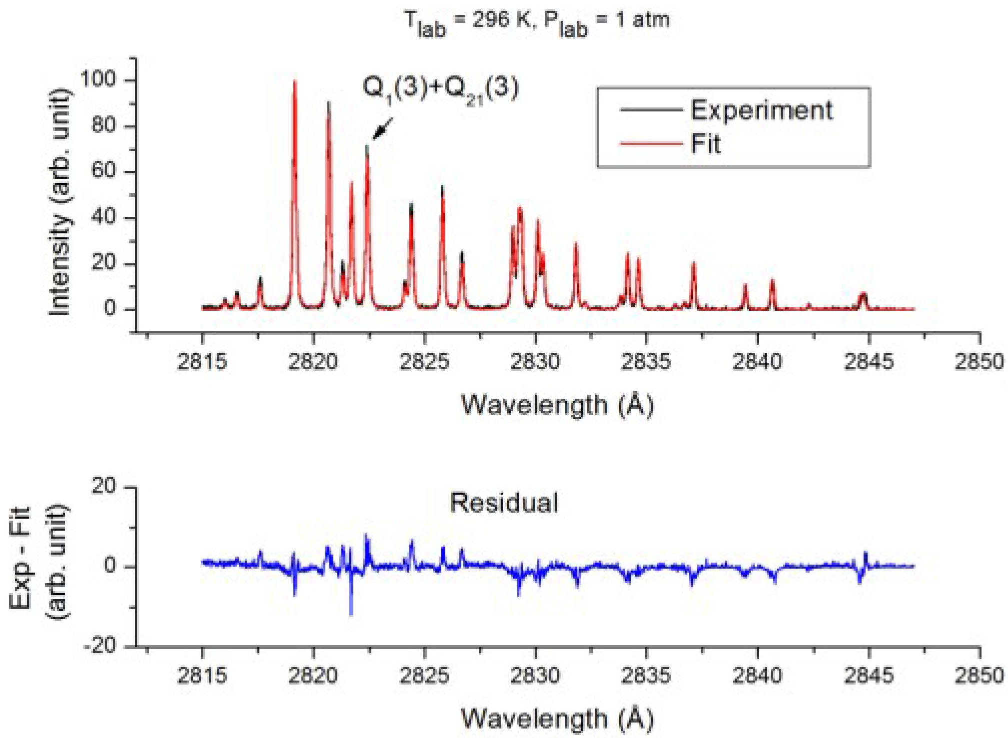
OH radical



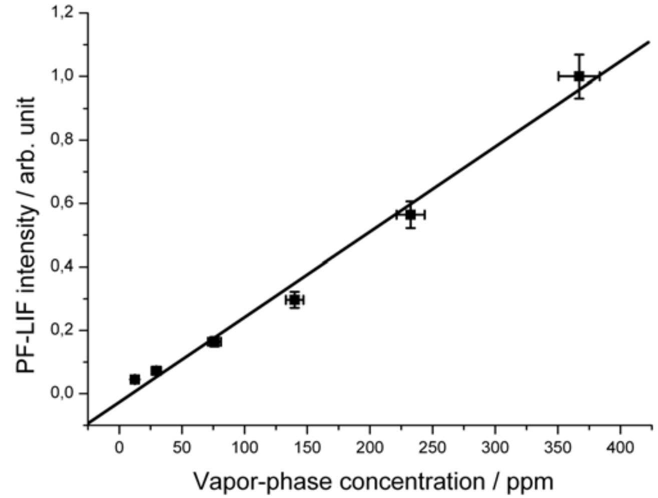
Hydrogen peroxide

H_2O_2 detection using PF-LIF

Excitation scan

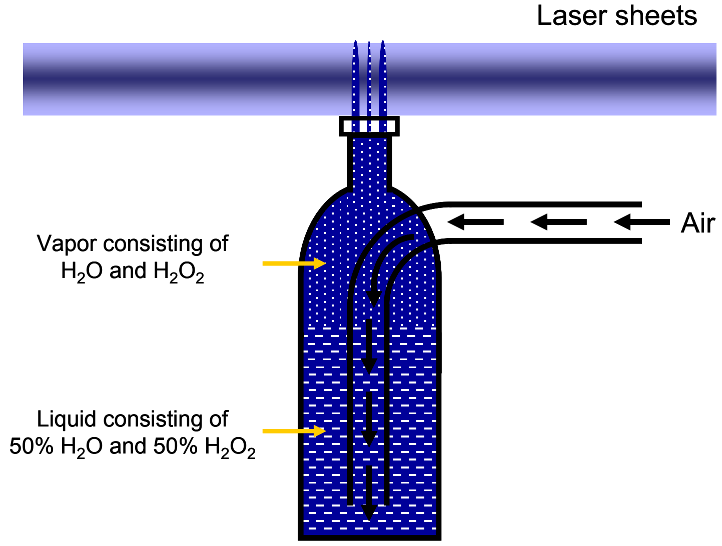


Signal vs $[H_2O_2]$ (g)

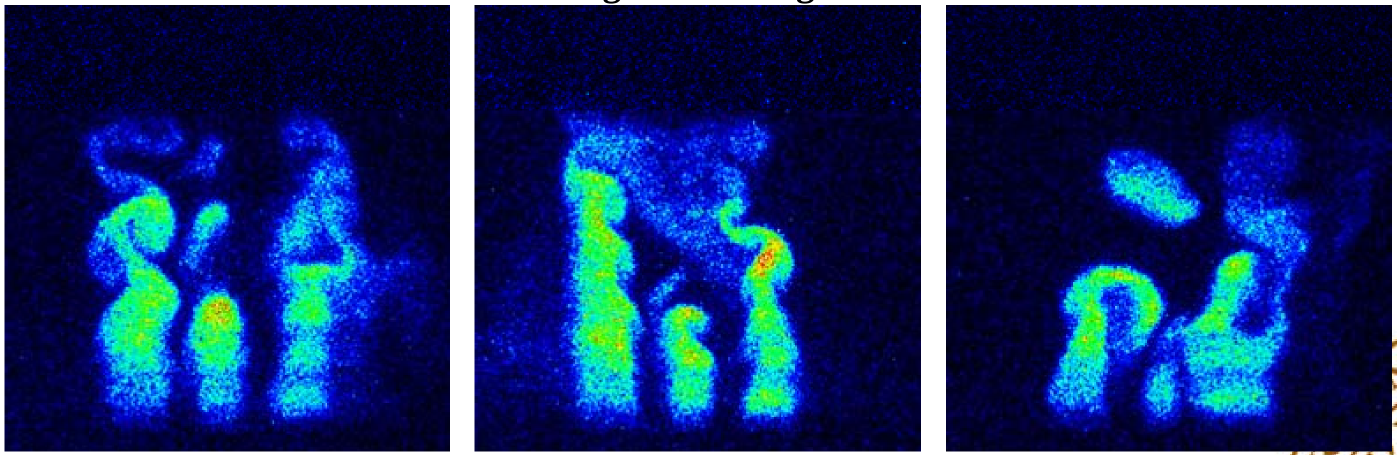


Johansson *et al.*, Appl. Spectr. **62**, 66-72 (2008).

PF-LIF imaging of H_2O_2



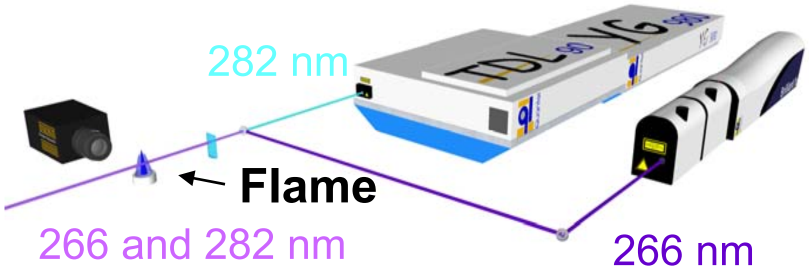
Single-shot images



Johansson *et al*., in The Conference on Lasers and Electro-Optics (CLEO)/The International Quantum Electronics Conference (IQEC) (Optical Society of America, Washington, DC, 2009), presentation CThI4.

Measurement of the total H_2O_2 + HO_2 concentration

H_2/O_2 flame on welding nozzle ($\phi = 2.2$)



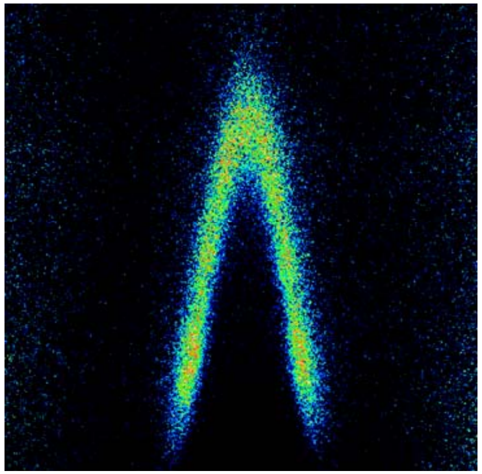
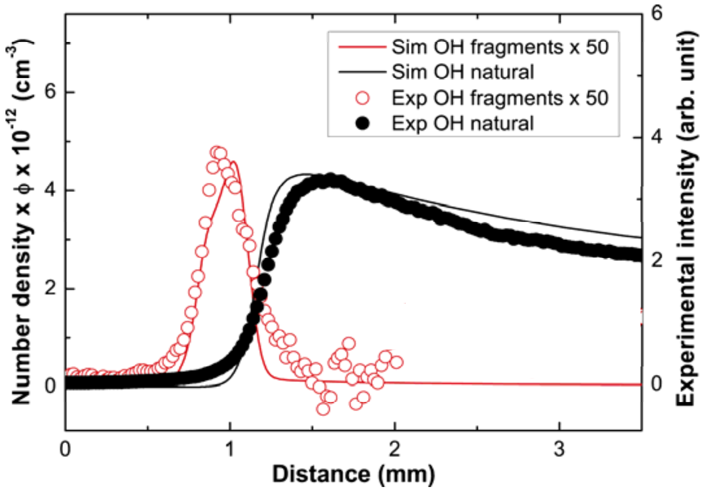
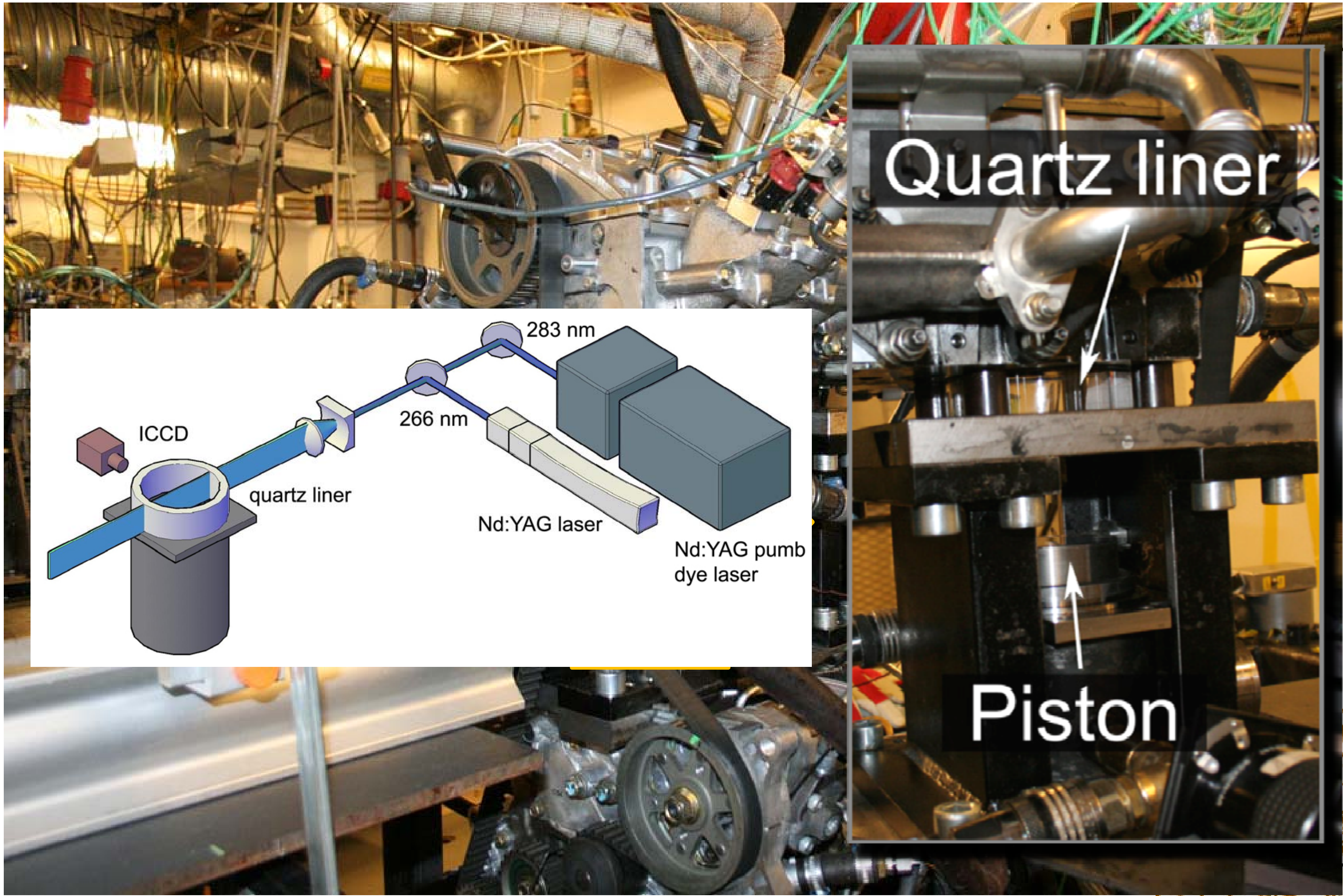


Image after subtraction of natural OH



Comparison with modeling

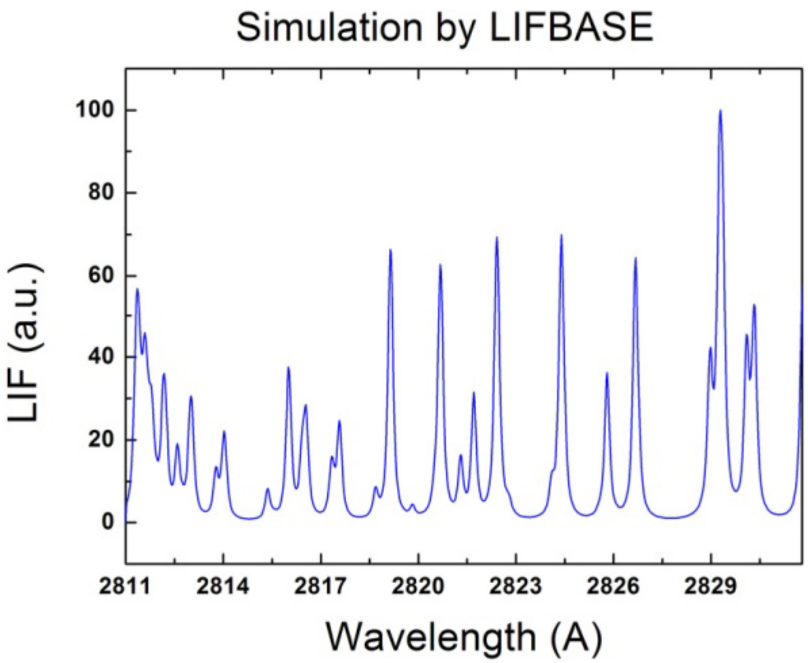
Application of PF-LIF in a HCCI Engine

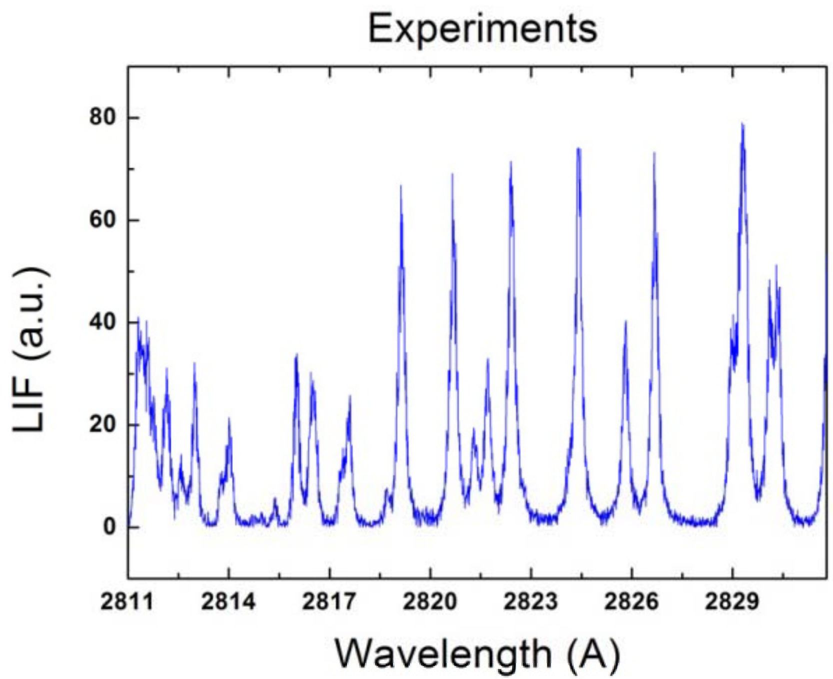


Bo Li et al.

PF-LIF Excitation Scan

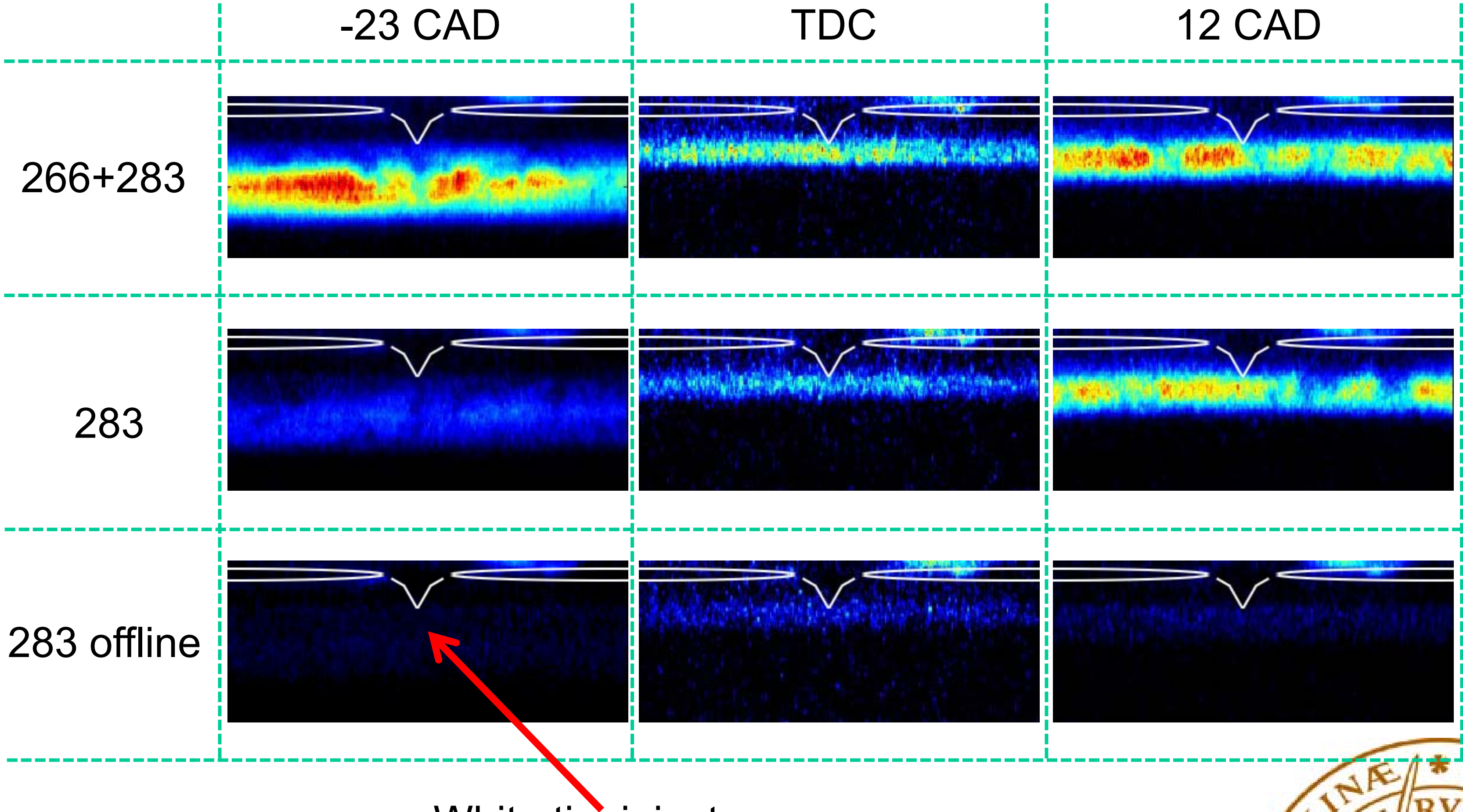
-23 CAD





Bo Li et al.

PF-LIF signal at different CAD



White tip: injector
Circles at each side: valves

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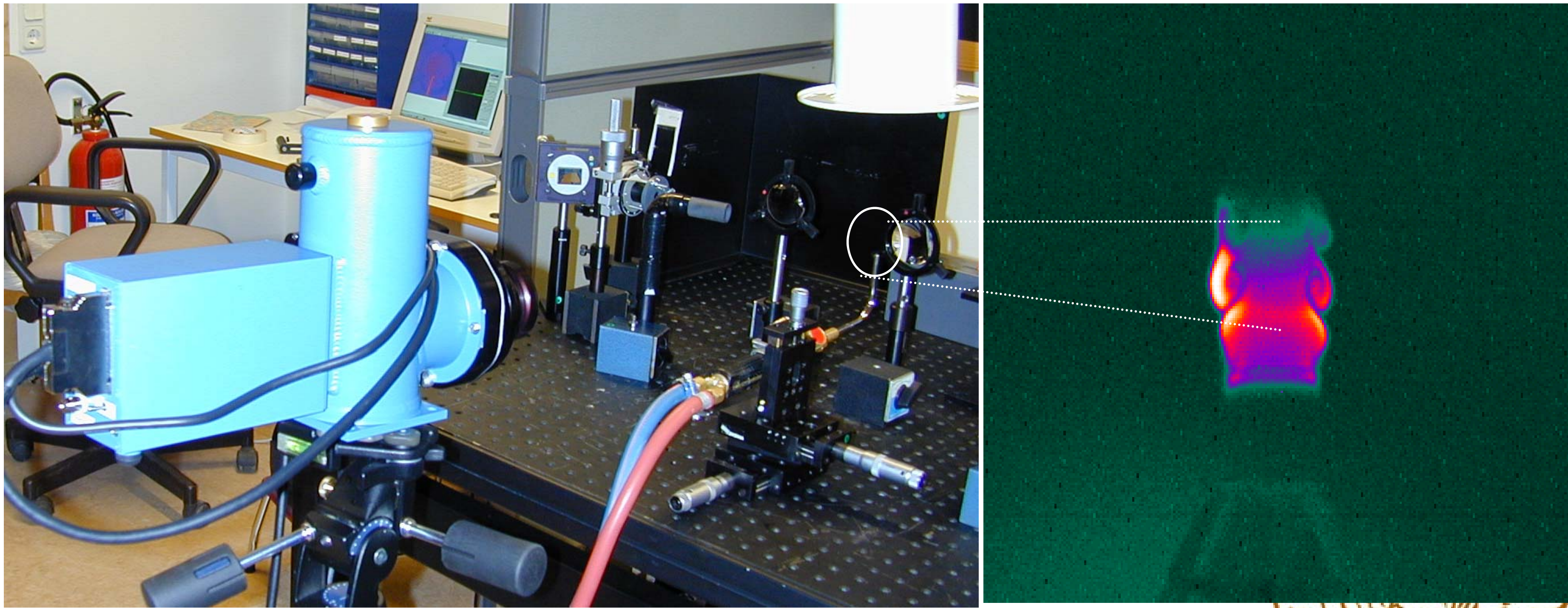
Future laser diagnostic challenges

- Multiple-parameter visualization (ρ, T, v, soot)
- 4D visualization (3D + t)
- Accurate species concentration measurements
- Quantitative characterization of sprays (gas/liquid distribution, temperature, droplet size,,,), dense sprays
- 2D velocity measurements without seeding
- Quantitative fuel visualization without seeder
- Accurate 2D temperature measurements
- On/near surface measurements (LIP, FRS, picosec.)
- Spatially resolved measurements using picosecond lidar
- Spatially resolved identification of different HC's,
- Measurements of EGR (CO_2)

LIF image of CO_2 (at 4.26 μm, right) from a 5 mm diameter nozzle



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Thank you for listening!

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