Mixture fraction measurements during the flame transmission at equipment of the type of protection “flameproof enclosure”

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Overview

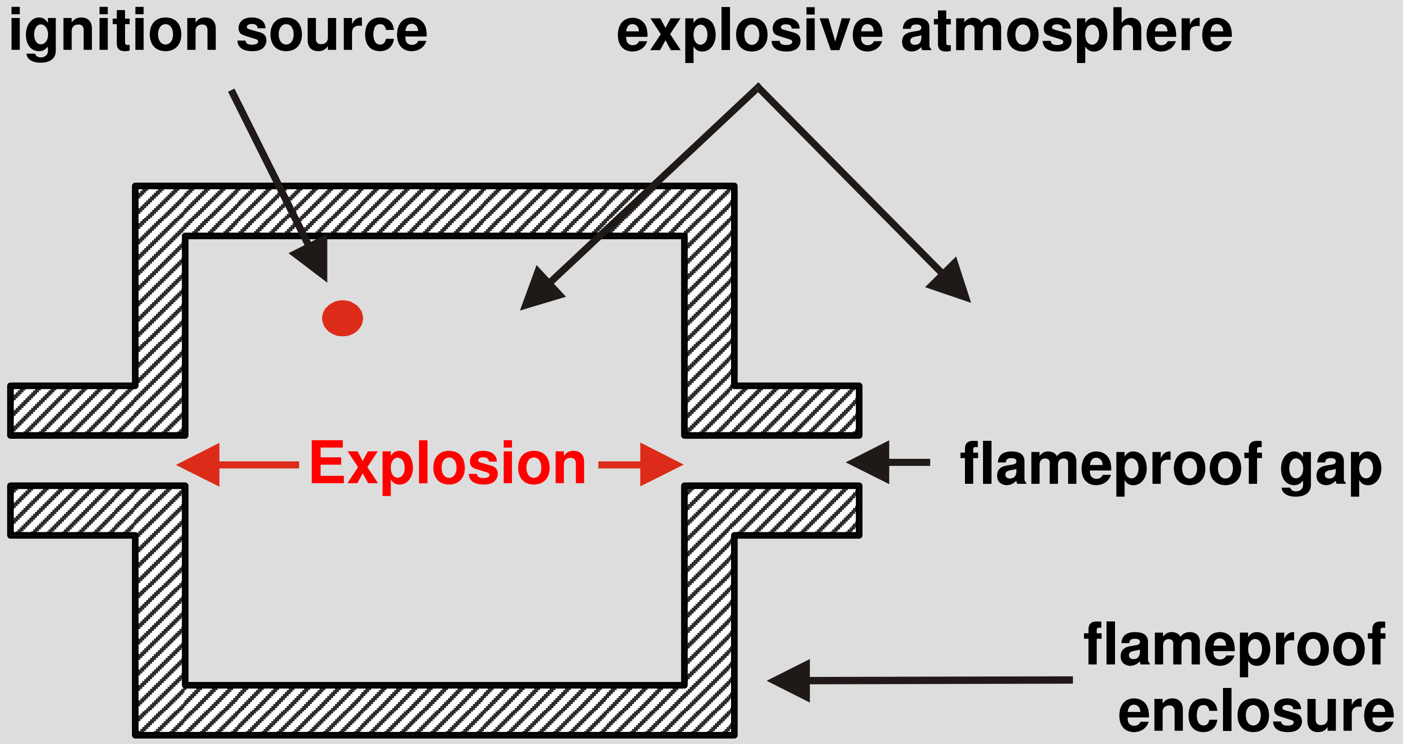
- Introduction
- Objectives
- Measurement Strategy
- Experimental Set-up
- Results
- Conclusions
- Outlook

Motivation

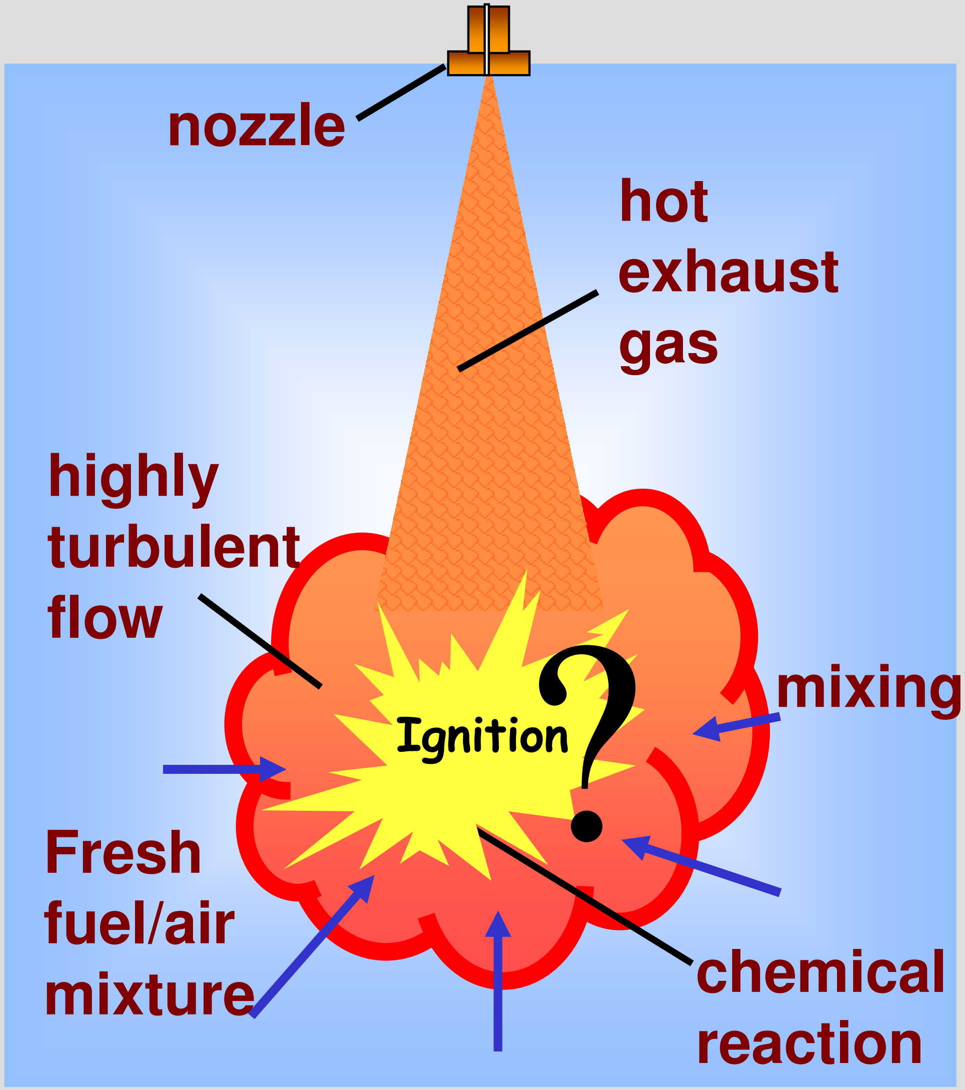
IEC 60079-1: Test for non-transmission of an internal ignition

Explosion Protection

- Flameproof Enclosures



Physical Processes



Influencing Factors

- Complex interaction between physical and chemical processes
- Competing influence of mixing, temperature and pressure on the ignition process
- Subsonic, sonic or super-sonic flow regimes

Objective

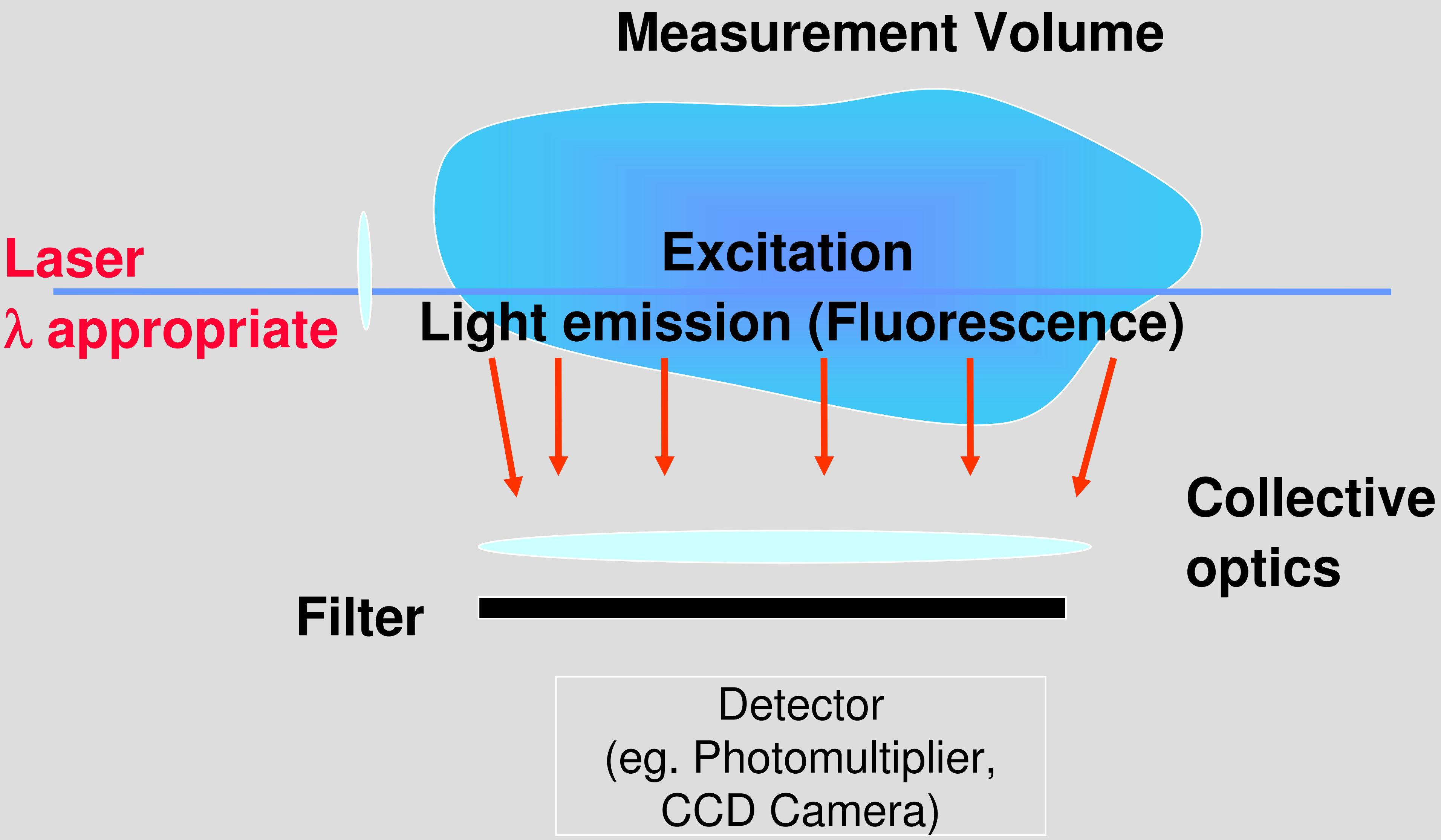
- Long term:
  - Develop a numerical model that can be used to predict hot jet ignition behaviour for a wide range of conditions.
- Short term:
  - Obtain empirical information about the mechanisms involved in the ignition process.
  - Use numerical simulations to guide the interpretation of the experimental results.

Experimental Method

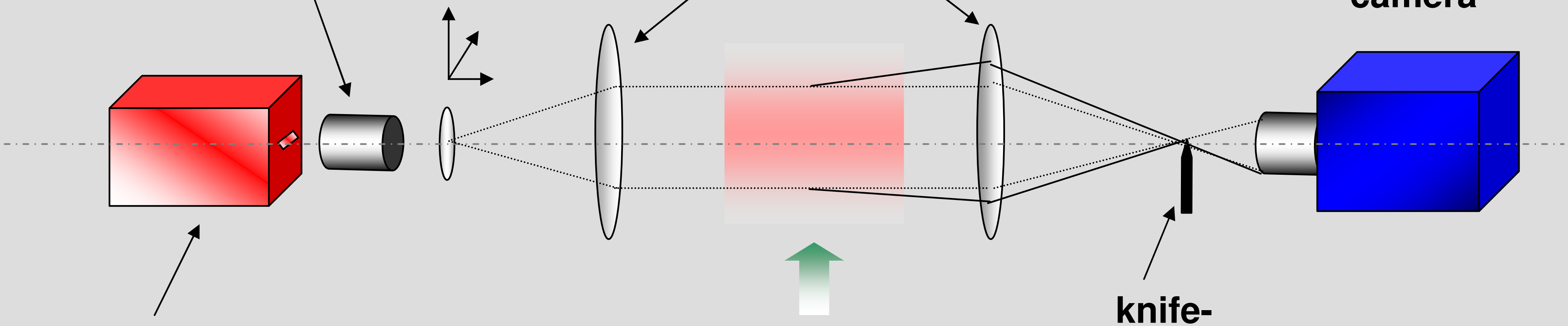
- Instationary and spatially inhomogeneous process
  - Spatially and temporally resolved information
- Highly sensitive to disturbances
  - Non-intrusive diagnostic method

- Study the temporal development of the jet structure
  - Use laser Schlieren visualisation
- Detect ignited regions inside the free jet flow
  - Visualise occurence of OH radical (OH-LIF)
- Information about the instantaneous mixing between the hot burned gas and the cold unburned fuel/air mixture
  - Mixture fraction measurements using NO as tracer species (NO-LIF)

Laser Induced Fluorescence



Laser Schlieren



Microscope objective lens

pinhole on three-axis translation stage

lenses

CCD camera

laser

observed medium

knife-edge

Combustion Cell

Requirements:

- simple, well-defined model
- optically accessible

First vessel:

Diameter = 60 mm

Length = 80 mm

Second vessel:

Volume = 12 dm^3

Mixture composition :

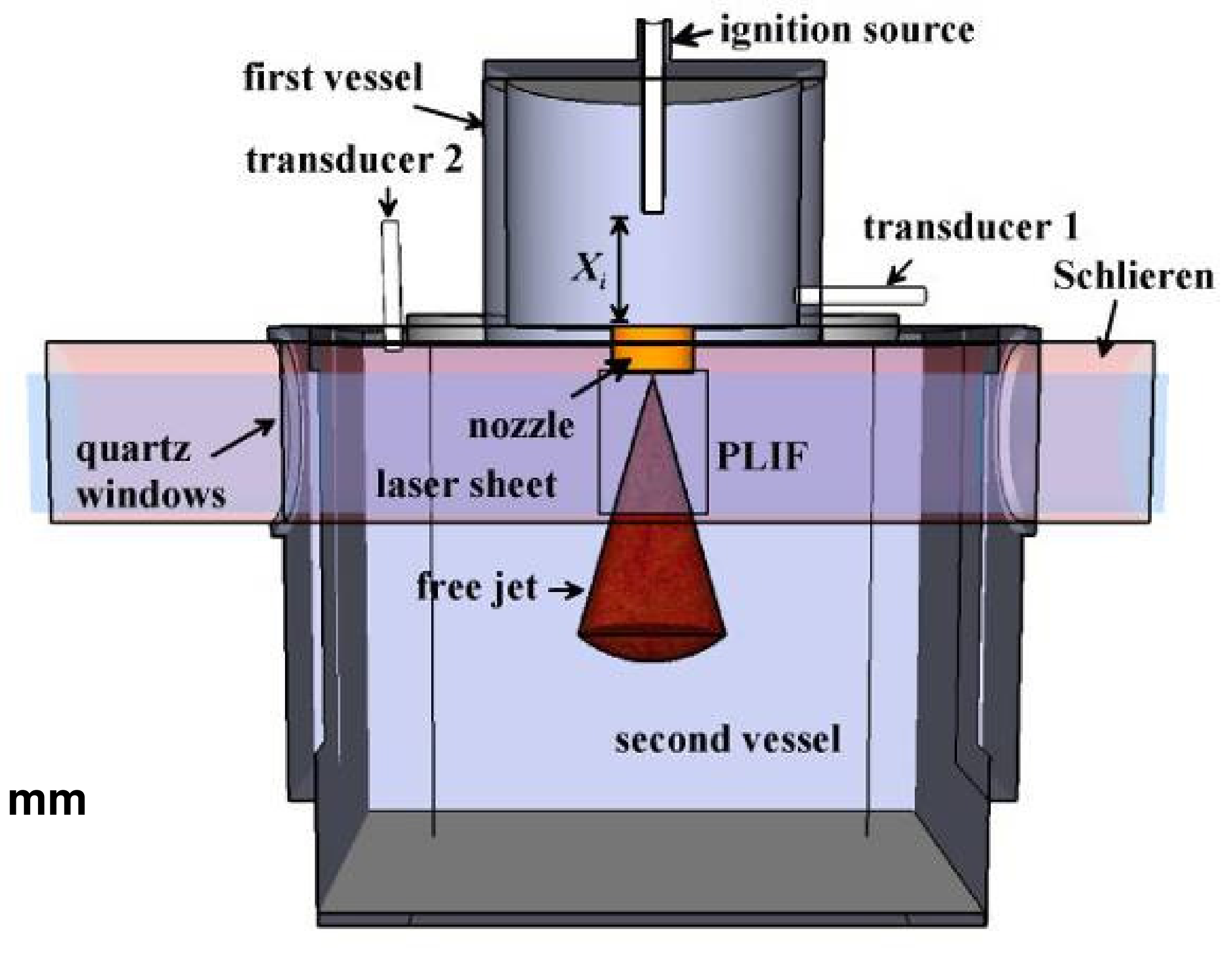
28% H_2 / 72 % Air

Nozzle:

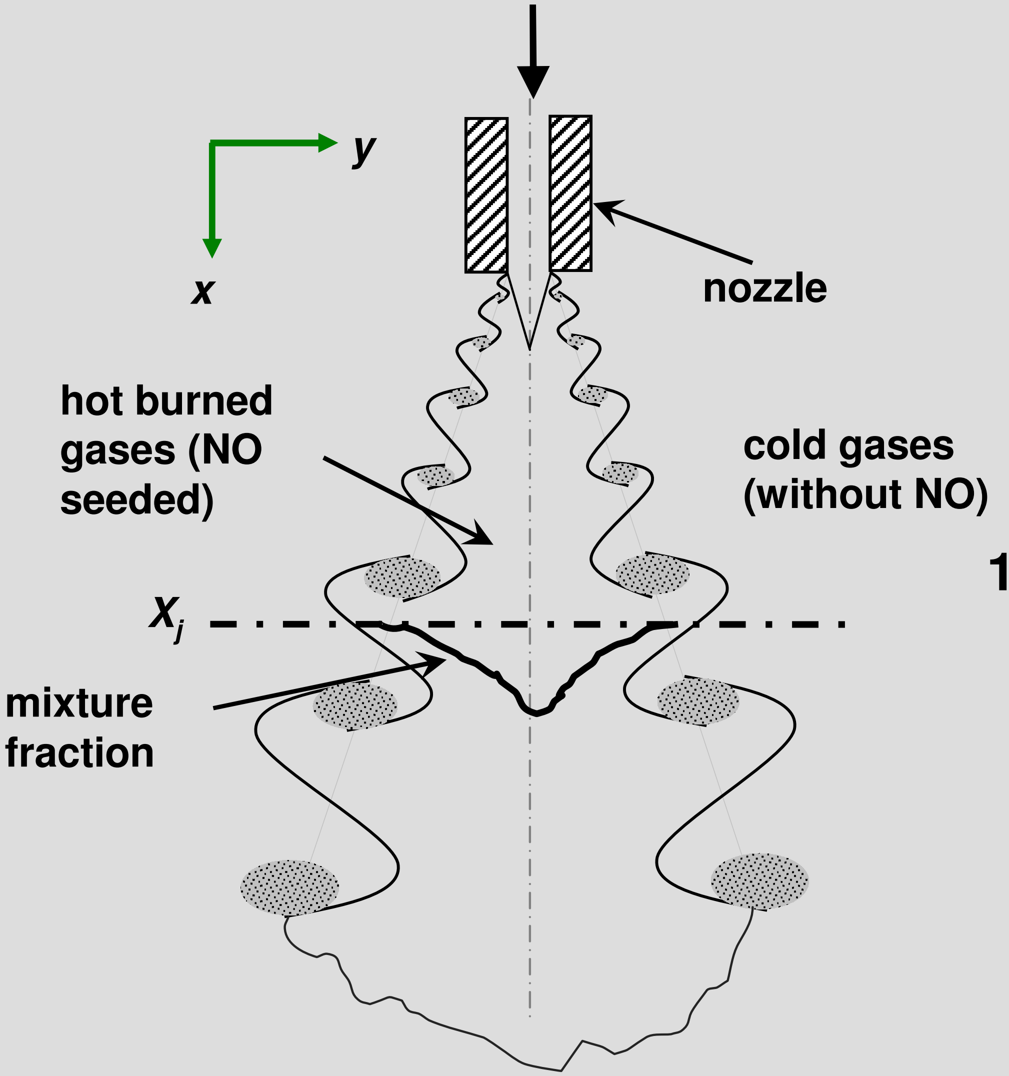
Length = 25 mm

Diameter = 0.7–1.3 mm

X_i = 24 – 56 mm



Mixture fraction (ξ)



Definition : mass fraction of all atoms originating from the hot jet

$$\xi = \frac{w_{NO} - w_{NO,c}}{w_{NO,h} - w_{NO,c}}$$

1 =

= 0

where:

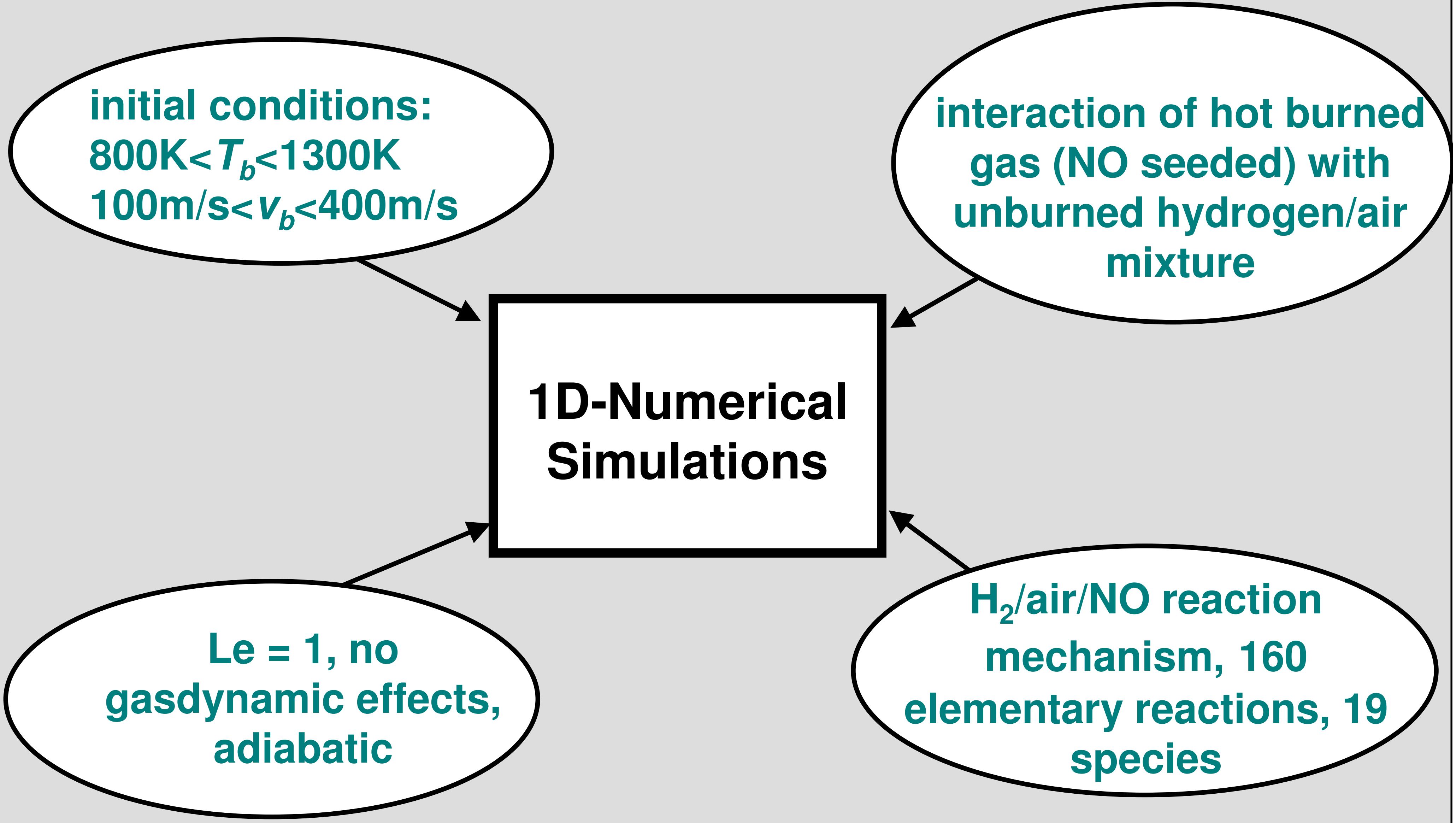
'w_{NO}' mass fraction of NO
'c' refers to the cold stream
'h' refers to the hot stream

Methodology

Perform numerical simulations of the system to obtain a large database of realisable state vectors $\psi = (T, p, x)$ during the process of mixing and re-ignition

sp. Location	Pr	T	wNO	wN2	wO2	wH2O
0.00E+00	1.00E+05	1.20E+03	9.93E-04	7.35E-01	5.73E-04	2.51E-01
3.45E-04	1.00E+05	1.20E+03	9.90E-04	7.35E-01	1.24E-03	2.50E-01
6.90E-04	1.00E+05	1.19E+03	9.85E-04	7.35E-01	2.47E-03	2.48E-01
1.03E-03	1.00E+05	1.18E+03	9.76E-04	7.35E-01	4.51E-03	2.46E-01
1.38E-03	1.00E+05	1.17E+03	9.62E-04	7.35E-01	7.68E-03	2.43E-01
1.72E-03	1.00E+05	1.15E+03	9.41E-04	7.35E-01	1.23E-02	2.37E-01
2.07E-03	1.00E+05	1.13E+03	9.13E-04	7.34E-01	1.85E-02	2.30E-01
2.41E-03	1.00E+05	1.09E+03	8.78E-04	7.34E-01	2.64E-02	2.21E-01
2.76E-03	1.00E+05	1.05E+03	8.34E-04	7.34E-01	3.61E-02	2.10E-01
3.10E-03	1.00E+05	1.01E+03	7.84E-04	7.34E-01	4.74E-02	1.98E-01
3.45E-03	1.00E+05	9.58E+02	7.28E-04	7.34E-01	5.99E-02	1.84E-01
3.79E-03	1.00E+05	9.03E+02	6.67E-04	7.34E-01	7.34E-02	1.68E-01
4.14E-03	1.00E+05	8.46E+02	6.04E-04	7.34E-01	8.75E-02	1.52E-01
4.48E-03	1.00E+05	7.89E+02	5.41E-04	7.34E-01	1.02E-01	1.36E-01
4.83E-03	1.00E+05	7.32E+02	4.78E-04	7.33E-01	1.16E-01	1.21E-01

Numerical Simulations



initial conditions:
$800K < T_b < 1300K$
$100m/s < v_b < 400m/s$

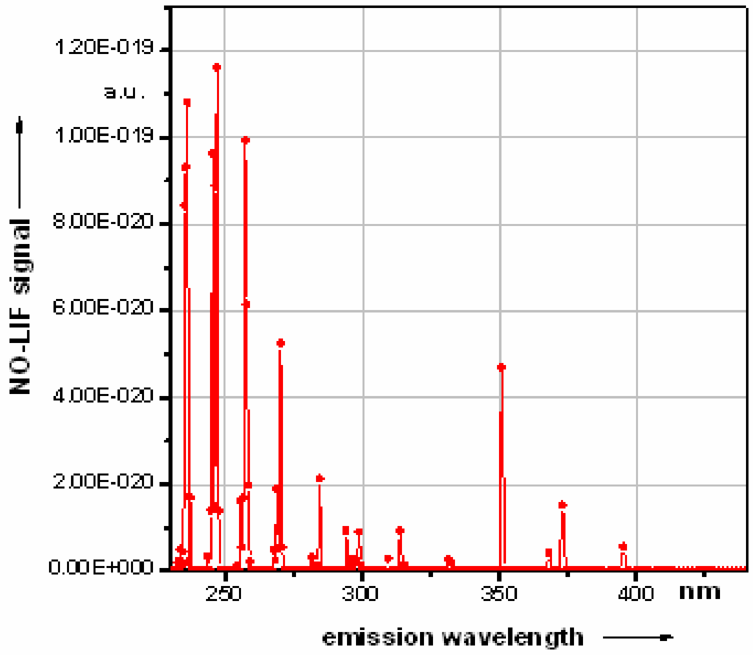
interaction of hot burned gas (NO seeded) with unburned hydrogen/air mixture

1D-Numerical Simulations

Le = 1, no gasdynamic effects, adiabatic

H_2/air/NO reaction mechanism, 160 elementary reactions, 19 species

Spectral Simulations

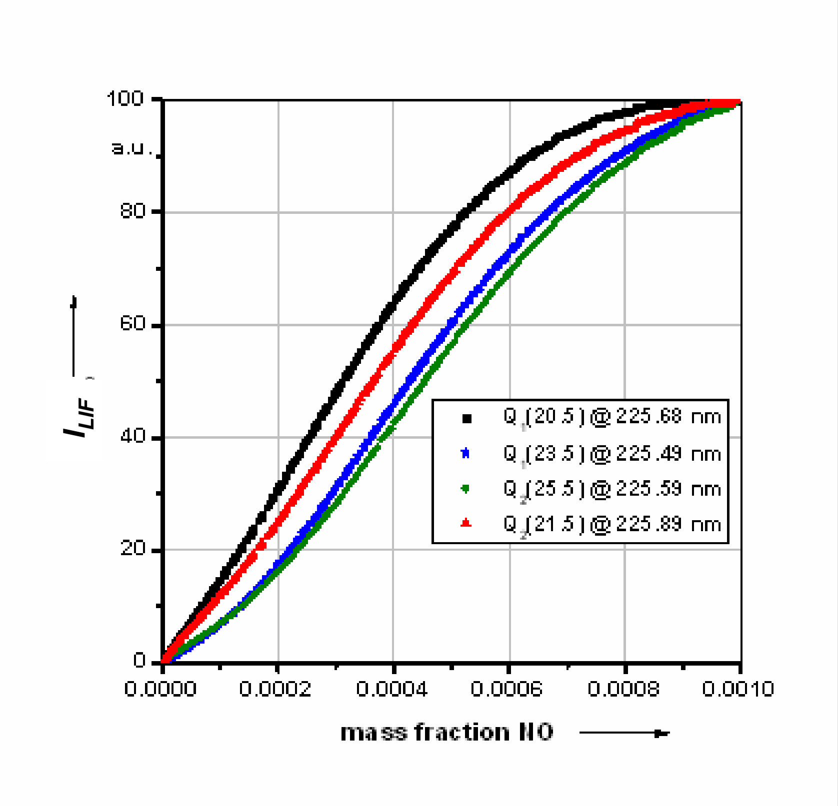


The state vectors so obtained are used for the spectroscopic simulation of corresponding NO-LIF-Signals using the program LIFSim*

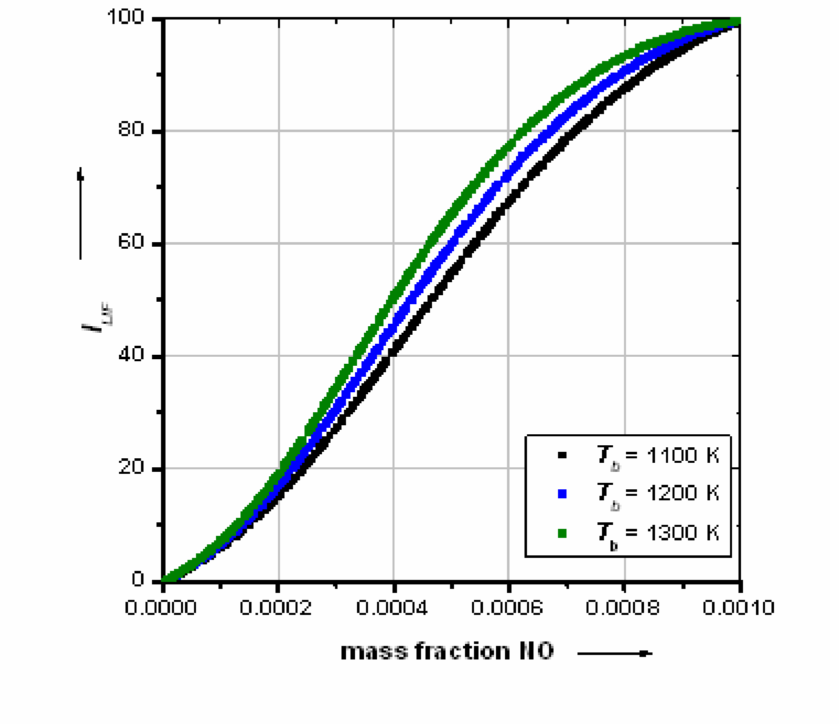
$$S(T,p,x_i) = I_{\mathrm{laser}} N_{\mathrm{NO}} f_{\mathrm{B}}(T) \sigma_{\mathrm{eff}} \frac{A_{21}}{A_{21} + Q_{21}(T,p,x_i)}$$

******W.G. Bessler, C. Schulz, V. Sick and J. Daily:*** **A versatile modelling tool for nitric oxide LIF specta. Proceedings of the Third Joint Meeting of the U.S. Sections of the Combustion Institute (2003) D33 1-6.**

Sharp correlation

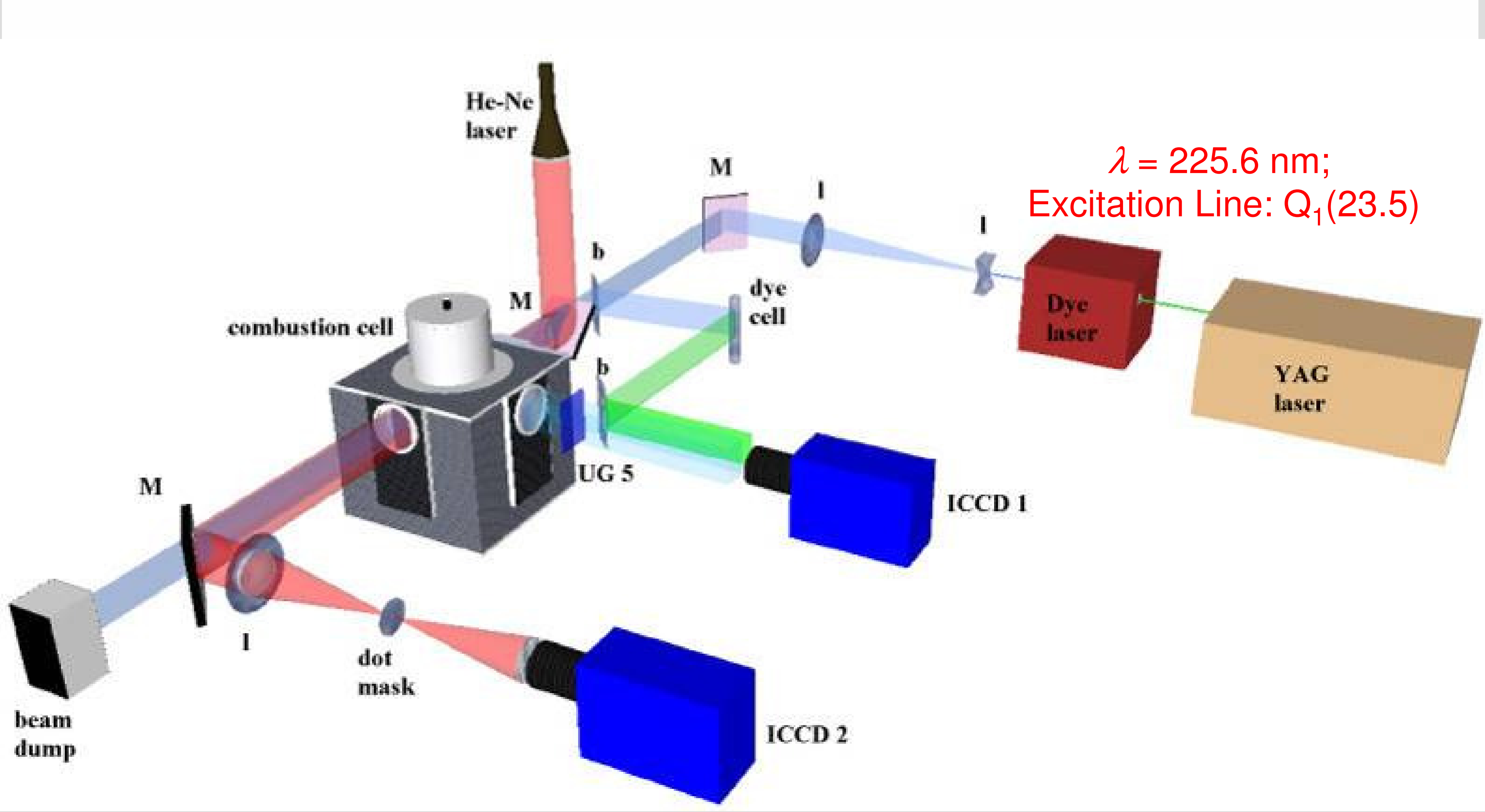


$Q_1(23.5)$



Experiments performed using excitation scheme with sharp correlations between I_{LIF} and NO mass fraction

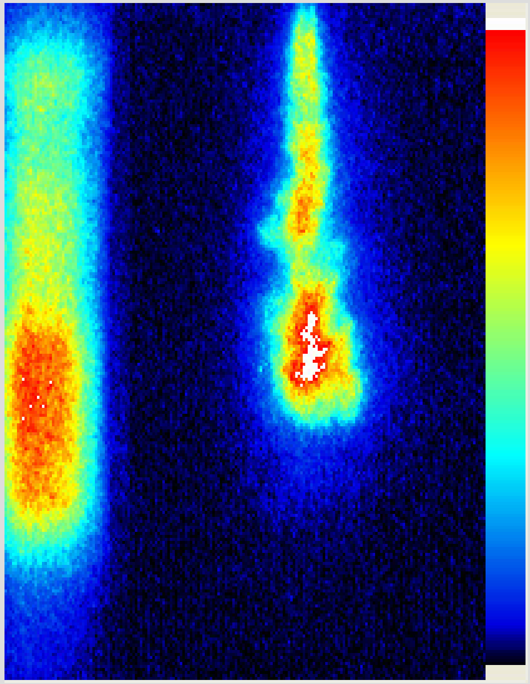
Schematic of the optical system



λ = 225.6 nm;
Excitation Line: $Q_1(23.5)$

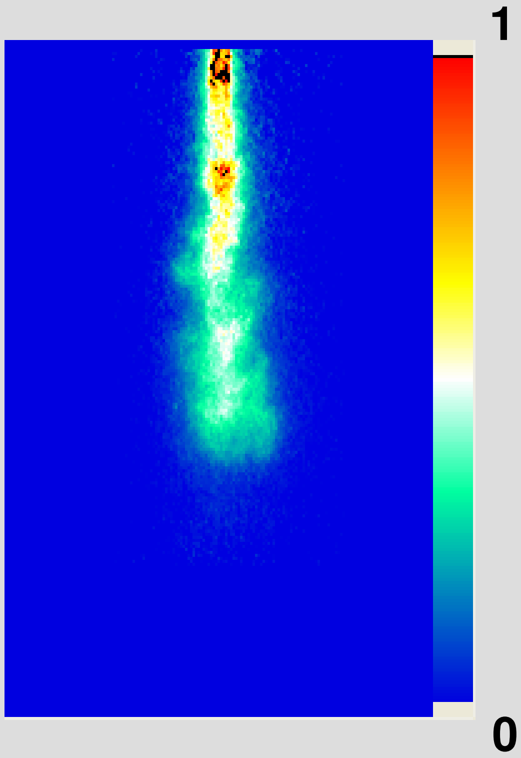
Mixture fraction maps

NO-LIF images converted to mixture fraction maps using the computed correlations



raw NO-LIF

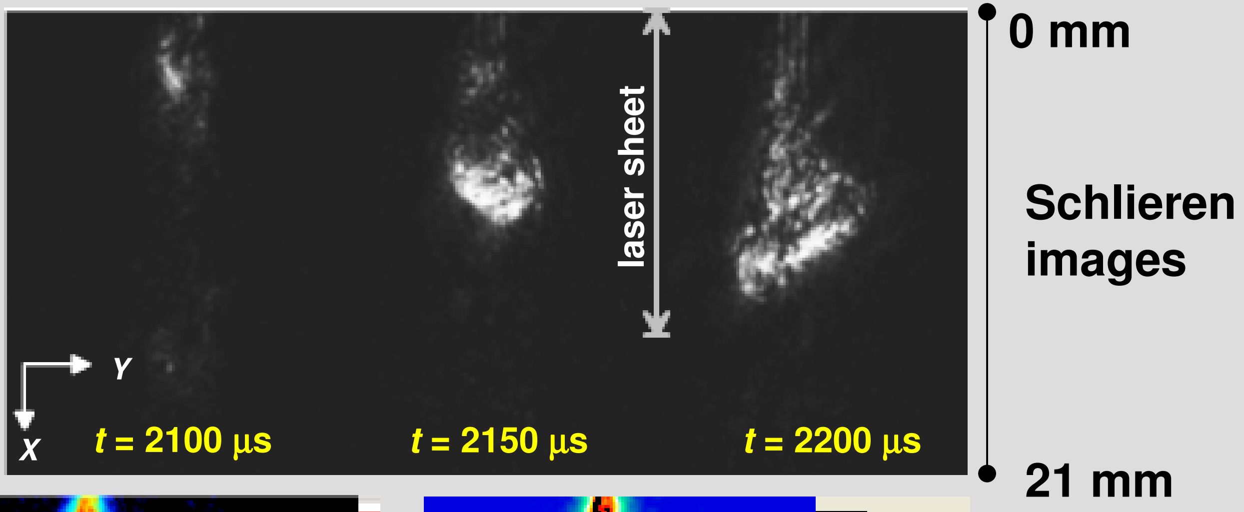
- Background noise corrections
- Laser sheet profile corrections
- Conversion to mixture fraction maps using correlations

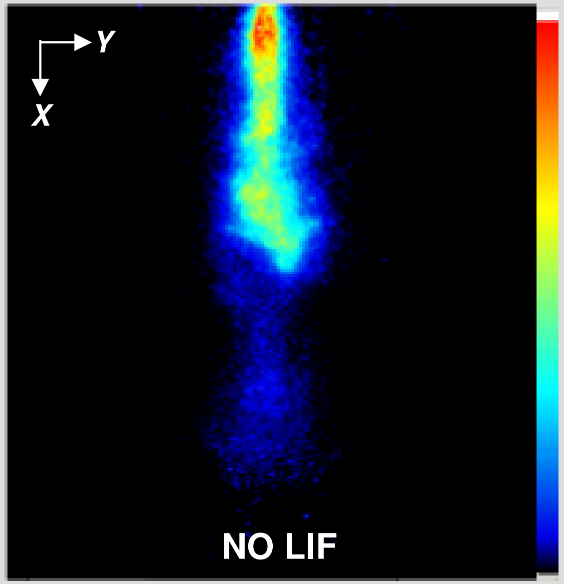


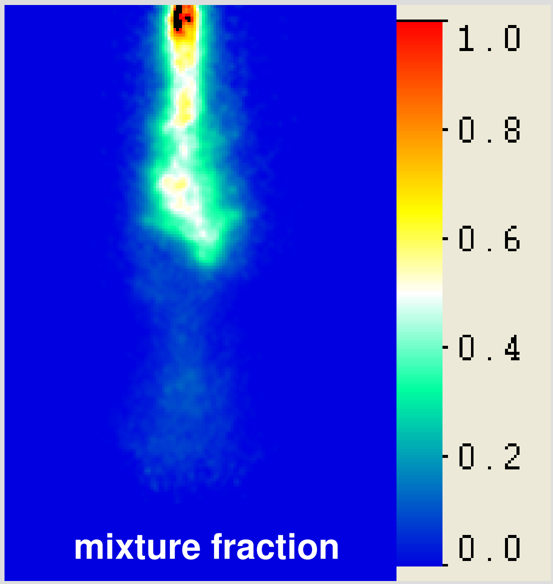
Mixture fraction

Case 1: Without ignition

$p_1/p_2 = 1.5$,
$d = 0.7$ mm

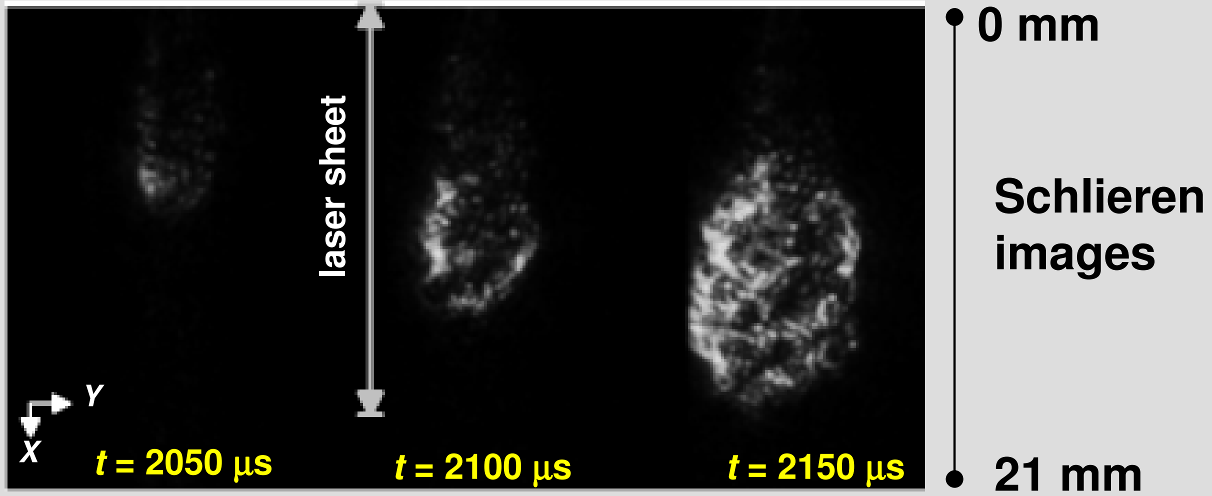


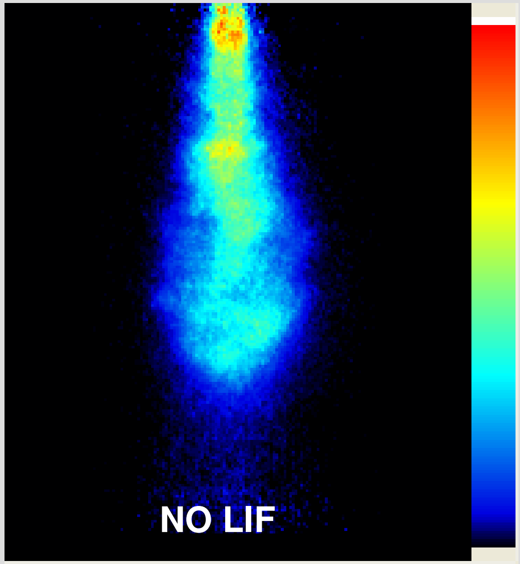


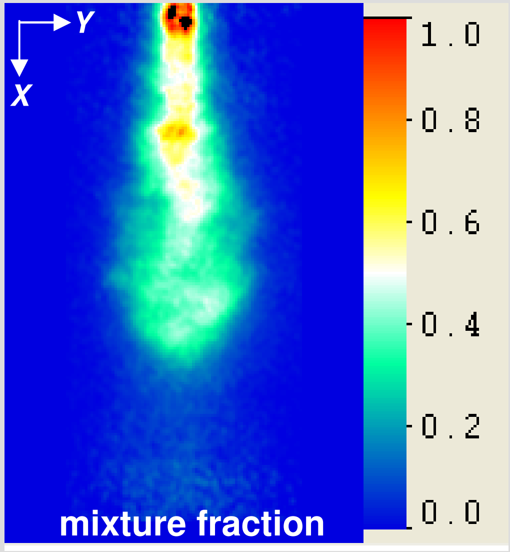


Case 2: With ignition

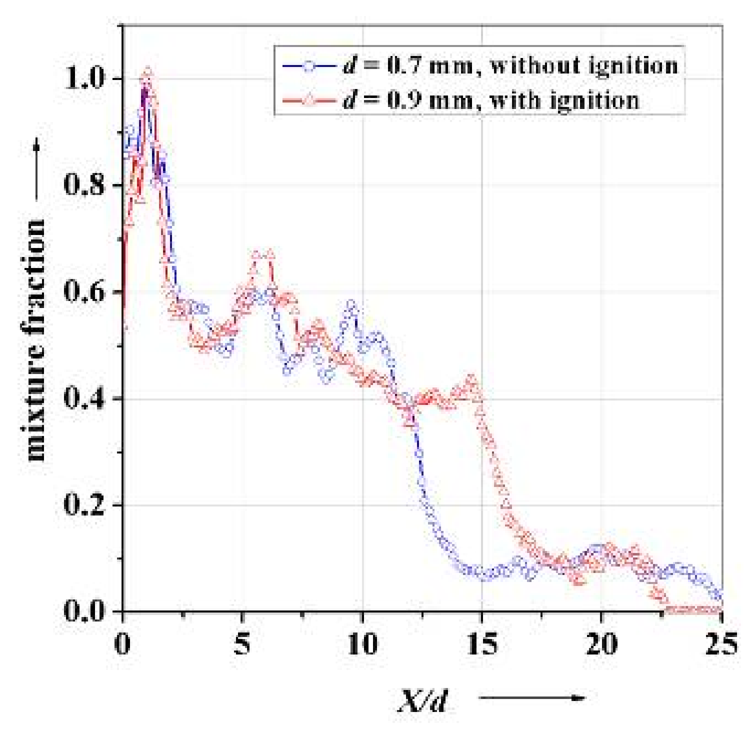
$p_1/p_2 = 1.44$,
$d = 0.9$ mm



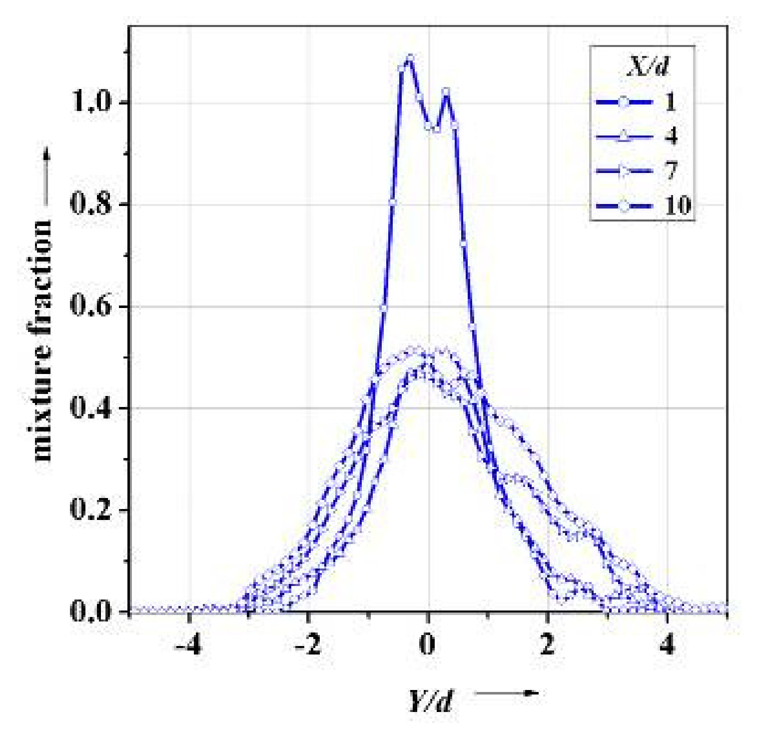




Mixture fraction profiles



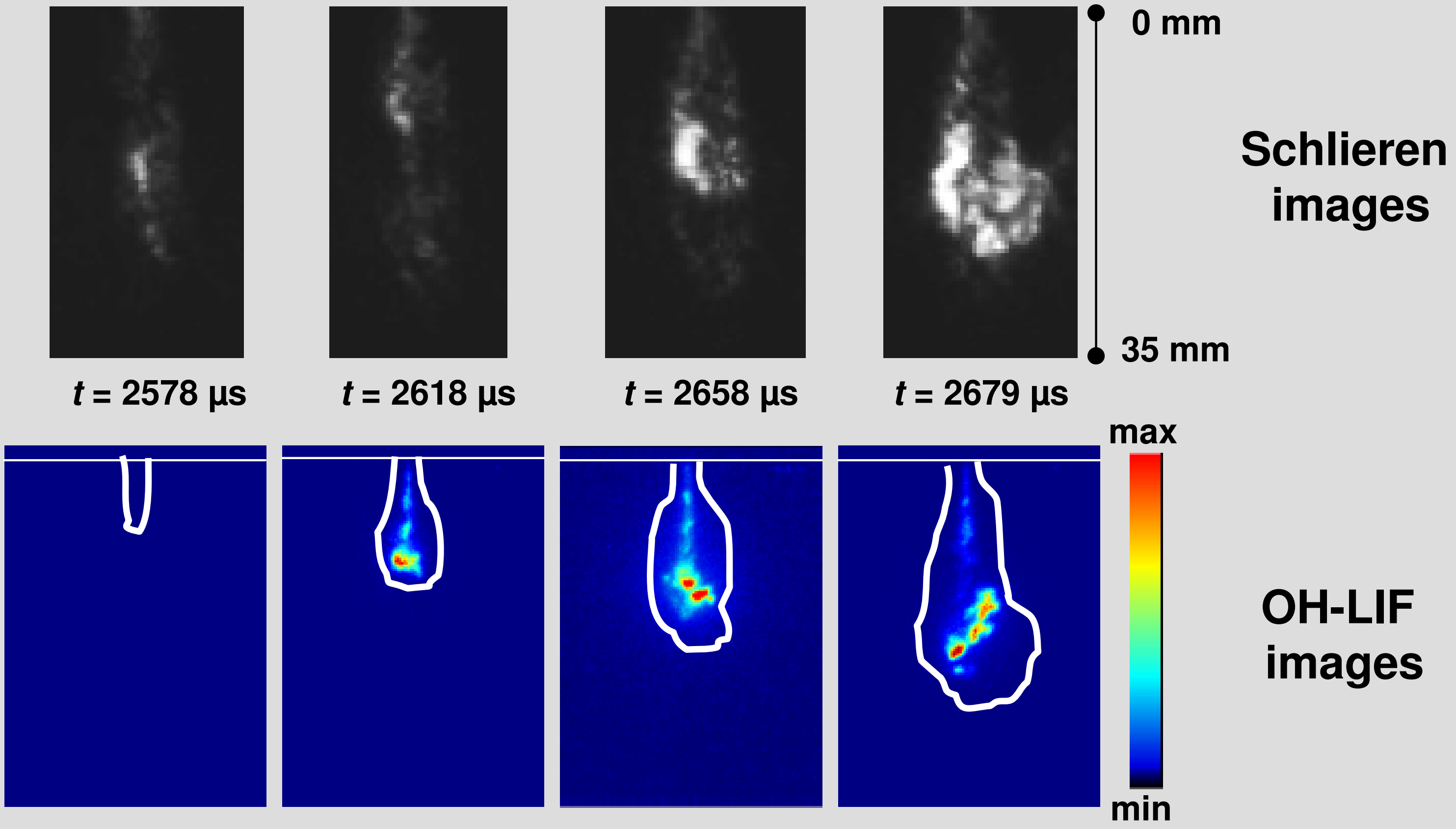
axial



radial, without re-ignition

- The axial profile shows a rapid decrease with downstream distance, indicative of the hot jet/unburned gas mixing
- The radial profile shows a progressive decay from the center value of the jet to the border, indicative of the rapid entrainment and turbulent mixing of the cold unburned mixture with the hot product jet

LIF of OH radicals

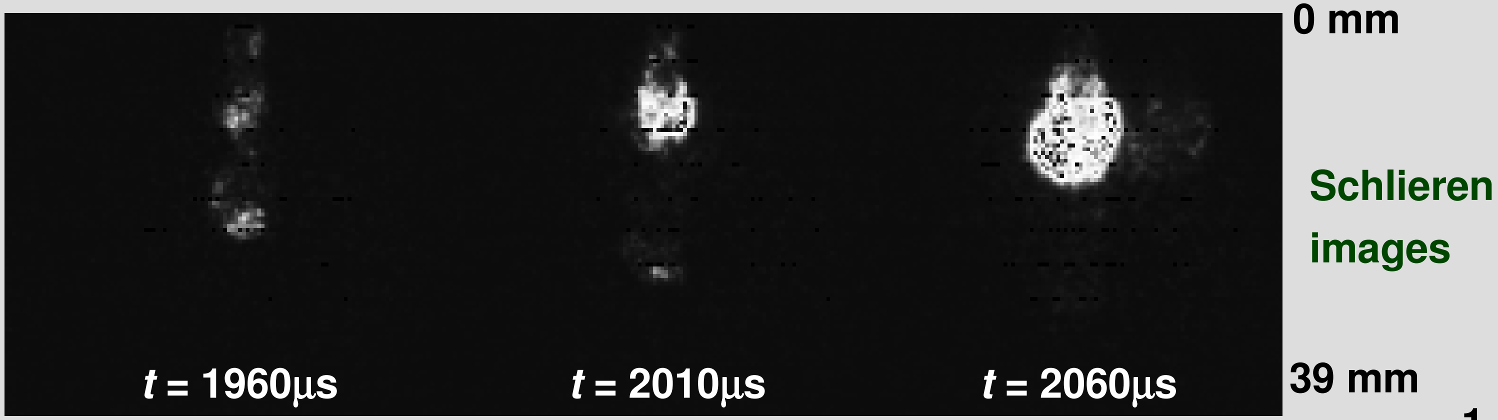


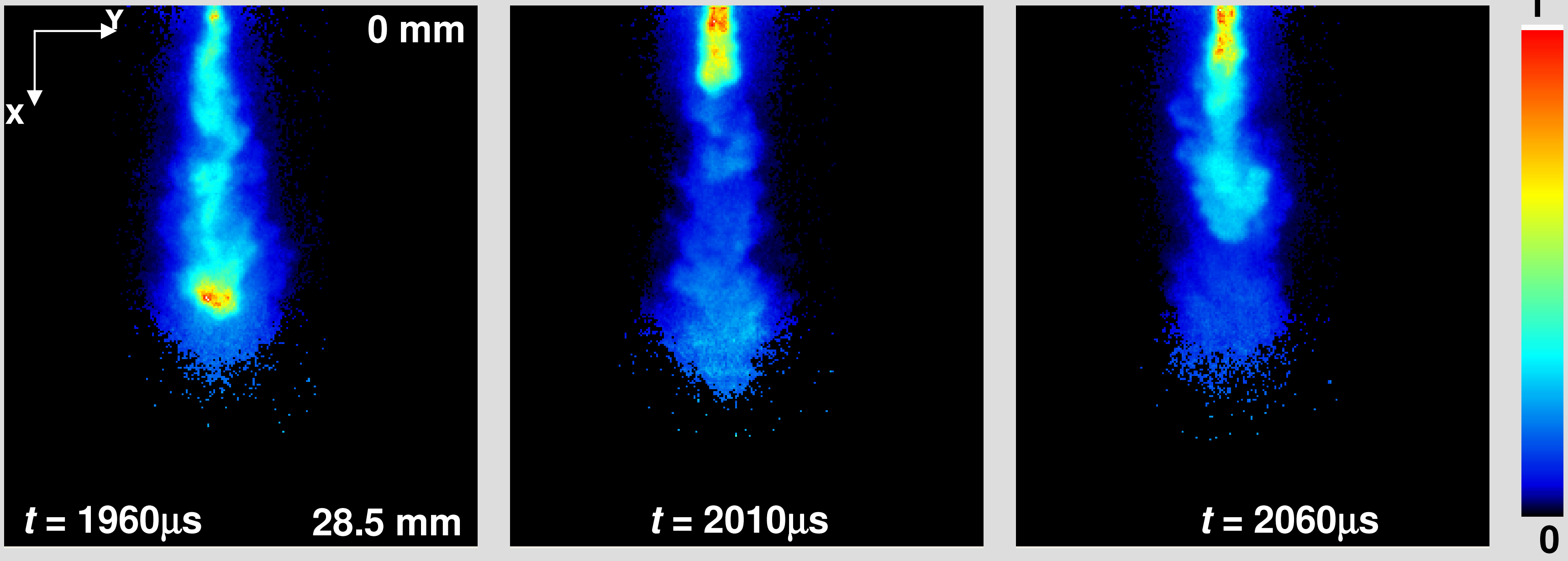
$p_1/p_2 = 2.06, \quad d = 1.0$ mm

Sadanandan, R. et al.: Proceedings of the Combustion Institute (2006) **31** 719-726

Limitations

$X_i = 24$ mm, $p_1/p_2 = 1.44$, $d = 0.8$ mm





Summary and Conclusions

- A novel measurement method has been developed for the instantaneous, quantitative, 2D and spatially resolved measurement of mixture fraction maps.
- The method is based on numerical simulations and spectroscopic modeling.
- Computed correlations between NO mass fractions and LIF signals are used to deduce mixture fraction profiles from NO-LIF images.
- Quantitative, planar instantaneous mixture fraction maps during the ignition of hydrogen/air mixtures by hot jets can be obtained.
- The method is applicable in cases where ignition and subsequent combustion has not raised the temperature to too high levels (< 1300 K).
- An alternative excitation scheme or a simultaneous second measurement is necessary to include those cases.