Temperature measurements in turbulent flames using Raman spectroscopy

Wolfgang Meier

German Aerospace Center (DLR), Stuttgart

EMPRESS Workshop

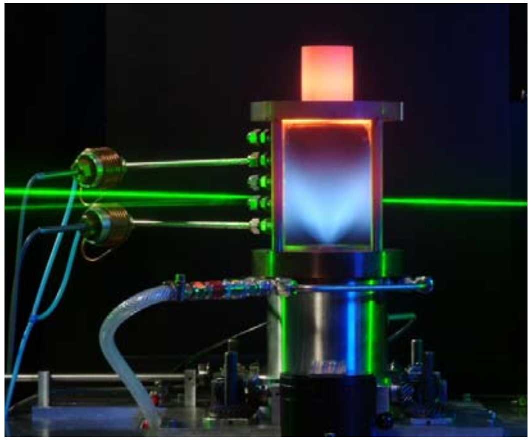
March 22, 2017, Glasgow, UK

DLR

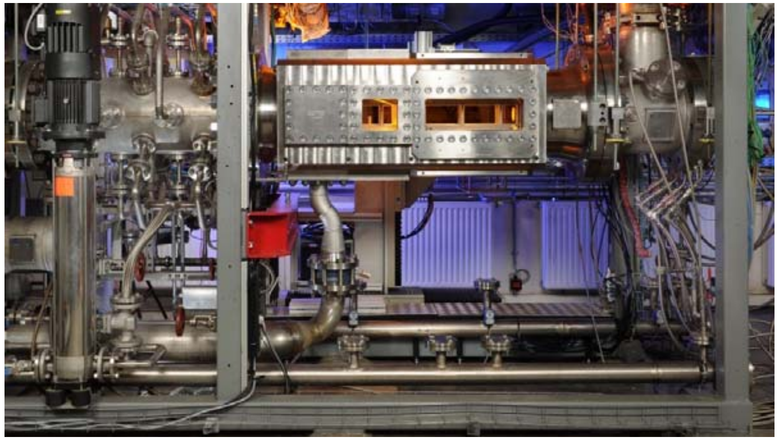
Combustion diagnostics at DLR Stuttgart

Work is focused on gas turbine combustion

- Pressures 1 – 30 bar
- Thermal powers 5 kW – 1 MW
- Temperatures 300 – 2500 K
- Fuels: Methane, natural gas, hydrogen, ethylene, kerosene, oil



lab-scale burner



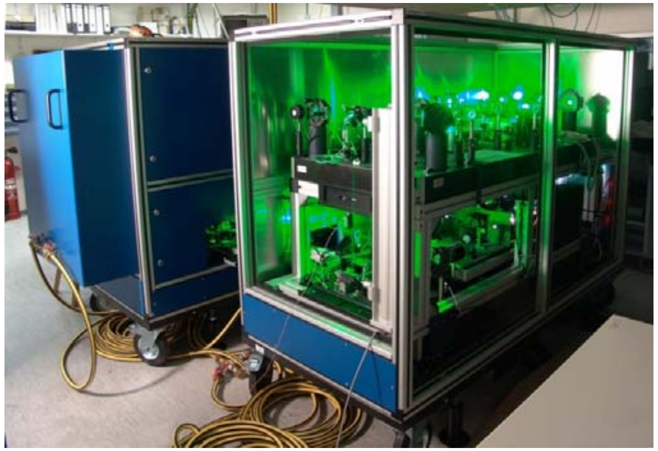
high-pressure test rig

Combustion diagnostics at DLR Stuttgart

Laser measurement techniques for

- Gas and droplet velocities (PIV, PDA)
- Species concentrations (LIF, Raman, LIBS, absorption spectroscopy)
- Gas temperatures (CARS, Raman, LIF)
- Surface temperatures (thermographic phosphors)
- Soot (LII)

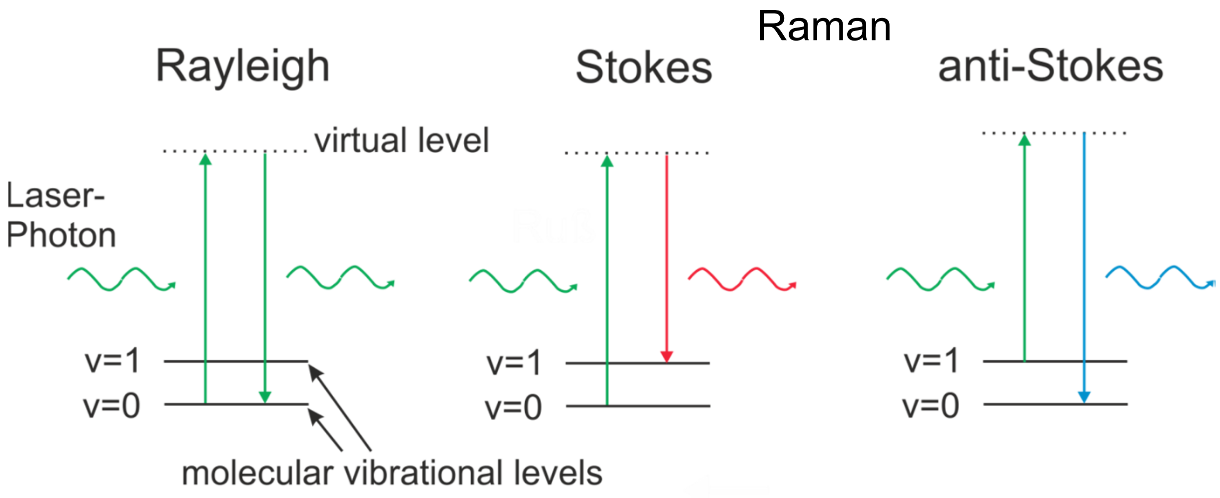
CARS laser system



Lasers for 1D Raman scattering

Fundamentals of laser Raman scattering

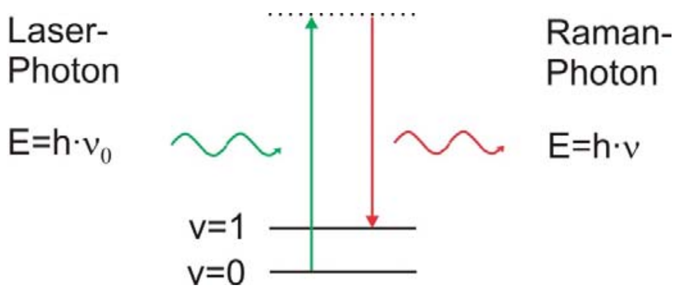
- Determination of species densities.
- Temperature is deduced in our applications from total number density
- Raman scattering is an inelastic scattering process of electromagnetic radiation at molecules (via polarizability).



Selection rules: $\Delta v = \pm 1$, $\Delta J = 0, \pm 2$ (J is rotational quantum number)

Fundamentals of Raman Scattering

- Excitation can be performed by arbitrary wavelength, because it is no resonant excitation process.
- All molecular species can be excited simultaneously with one laser.
- Wavelength shift of the Raman-scattered light corresponds to energy of a vibrational energy quantum of the molecule.
- Wavelength shift is characteristic of molecular species.



$$\Delta E = h \cdot (\nu_0 - \nu) = E_{vib}$$

Fundamentals of Raman Scattering

Signal intensity

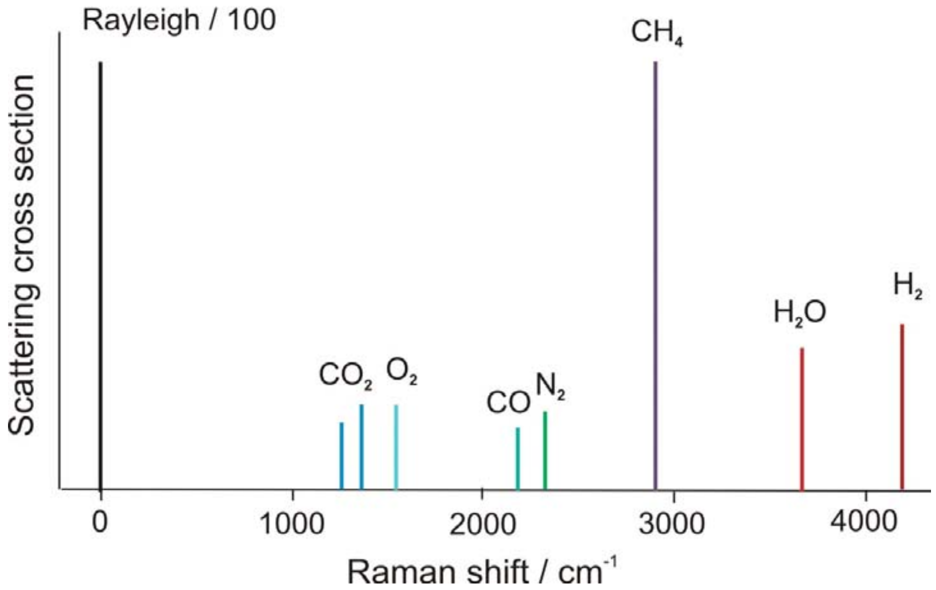
$$I_{RS} = I_L \cdot N_i \cdot d\sigma/d\Omega \cdot \Omega \cdot \varepsilon \cdot q \cdot L$$

I_{RS} : detected Raman intensity
I_L : laser intensity
N_i : molecular density of species i
$d\sigma/d\Omega$: differential scattering cross section
Ω : solid angle of detection optics
ε : optical efficiency
q : quantum efficiency of detector
L : length of measuring volume

- Molecular density can be determined from the Raman signal.
- The constants are typically determined by calibration measurements.

Fundamentals of Raman Scattering

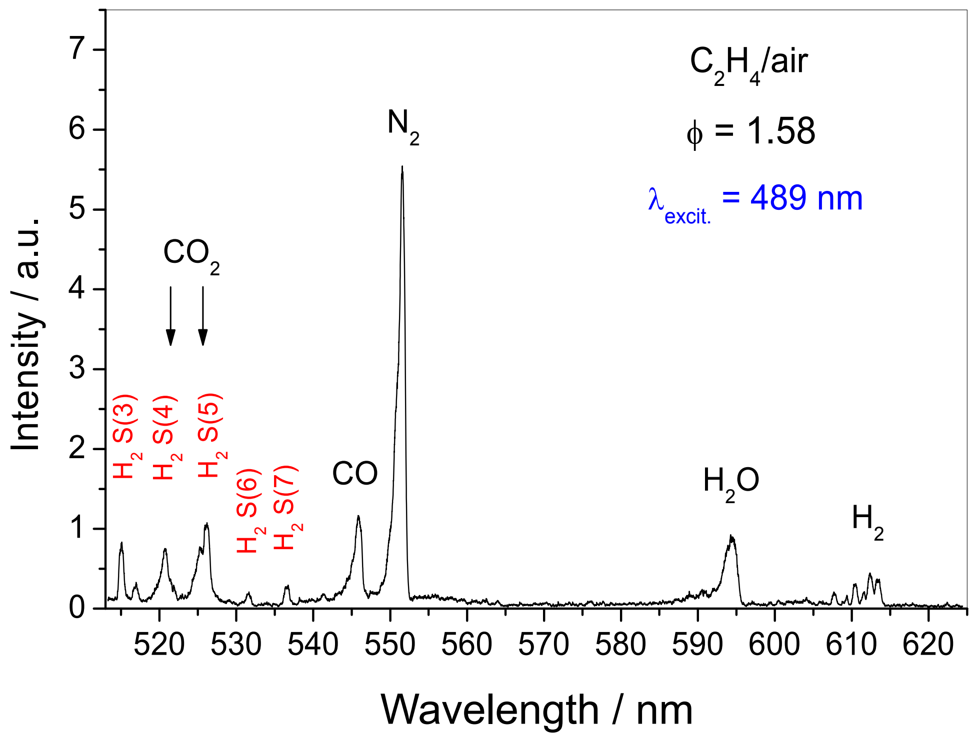
Raman-shift and scattering cross sections of major species in flames



In principle, all these species can be detected simultaneously in flames

Fundamentals of Raman Scattering

Measured spectrum from a fuel-rich premixed ethylene/air flame.



Fundamentals of Raman Scattering

If all (major) species are detected simultaneously the total number density N_{total} can be determined:

$$N_{total} = \Sigma N_i$$

With knowledge of the pressure p the temperature can be determined via the ideal gas law:

$$T = p / (k \cdot N_{total}) \qquad \text{k: Boltzmann constant}$$

Temperature and major species concentrations can be determined simultaneously
→ wonderful measuring technique! But, …

Low signal levels, high laser power needed, only applicable in “clean” flames.

Calibration devices

- Cold and electrically heated gas flows, temperatures known from thermocouples.
- Flat laminar flames, temperatures known from CARS measurements.

Burner with sintered bronze matrix (McKenna type)

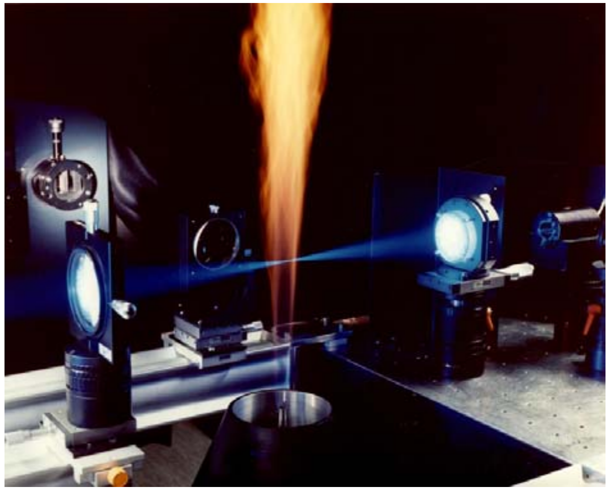
Lasers for Raman scattering

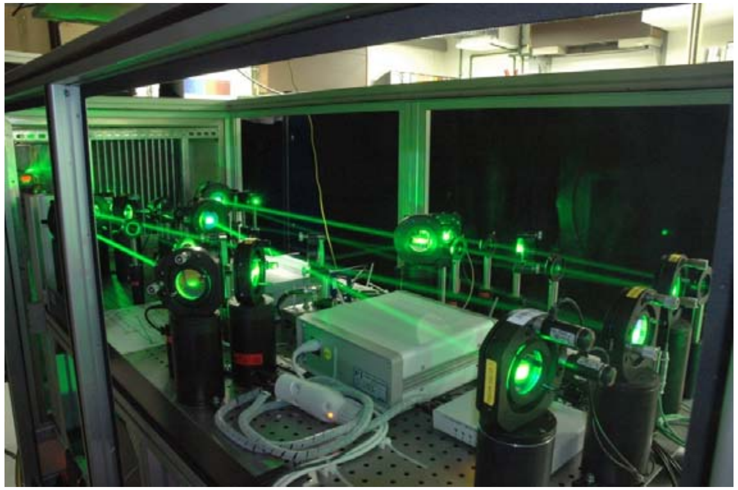
Flashlamp-pumped dye laser

- Pulse energy 2.5 J, pulse duration 2 μs, wavelength λ = 489 nm, repetition rate 5 Hz, only suited for point measurements

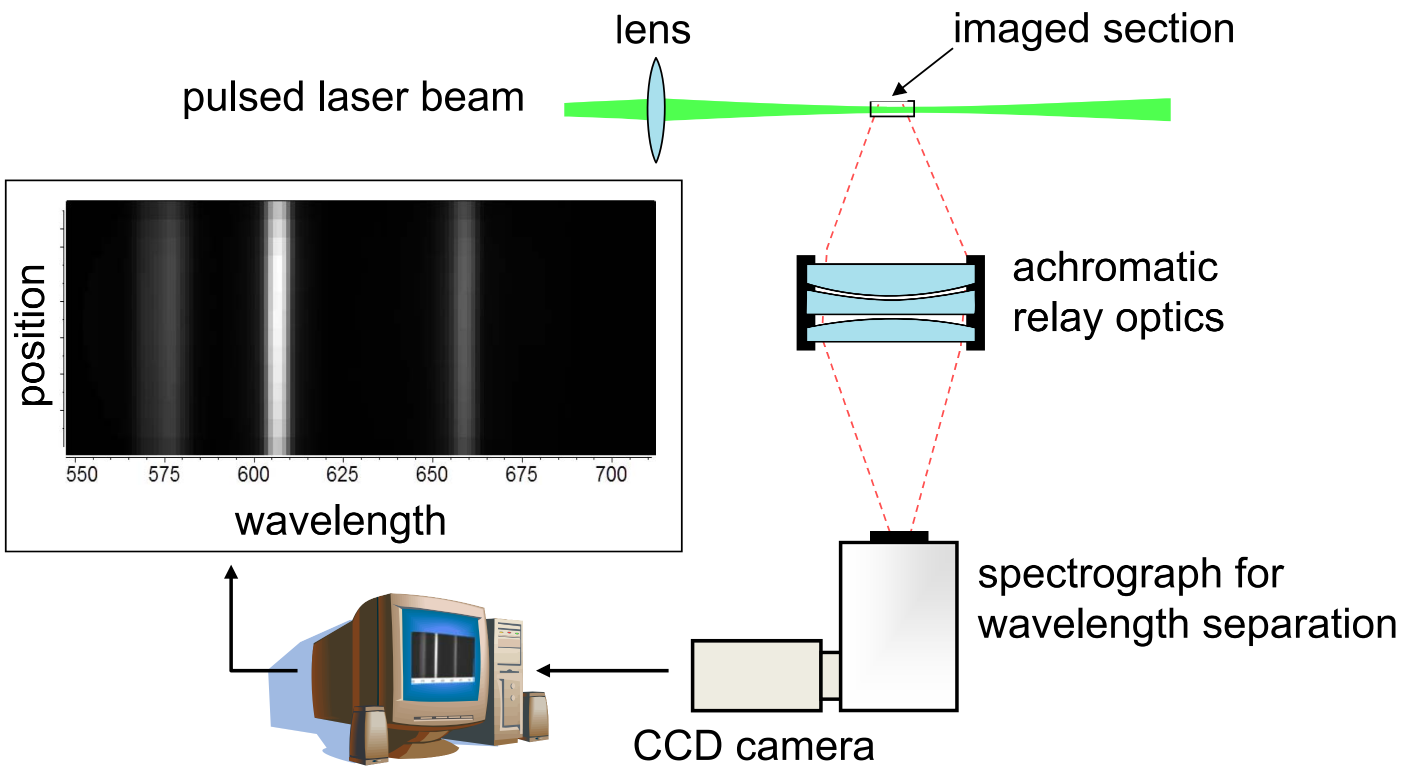
Nd:YAG laser cluster

- Pulse energy 1.7 J, pulse duration with pulse stretcher 350 ns, λ = 532 nm, repetition rate 10 Hz, suited for 1D measurements





Experimental setup for 1D Raman scattering



Spatial measurement resolution ≈ 0.5 mm

Measurement uncertainties

Systematic uncertainties

- Calibration procedure (T of calibration flames, flow meters, …)
- Laser pulse energy
- Drifts of alignment of optical setup
- For T: ±3-4%

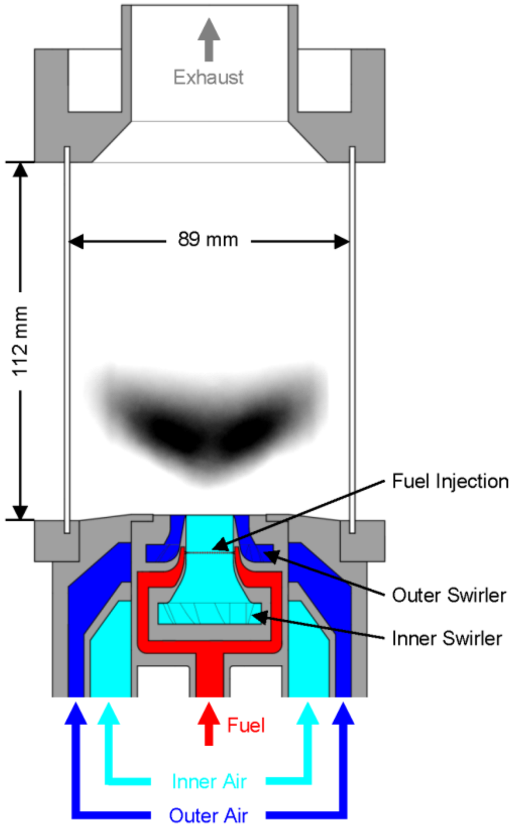
Statistical uncertainties of single shot measurement

- Shot noise of detected photons
- For T: ±2.5%

Uncertainties depend on experimental arrangement and flame condition.

Measurements in partially premixed CH_4/air swirl flames

Thermal power 25 kW



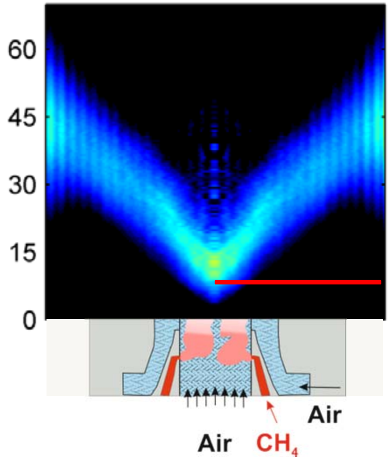
combustion chamber with quartz windows

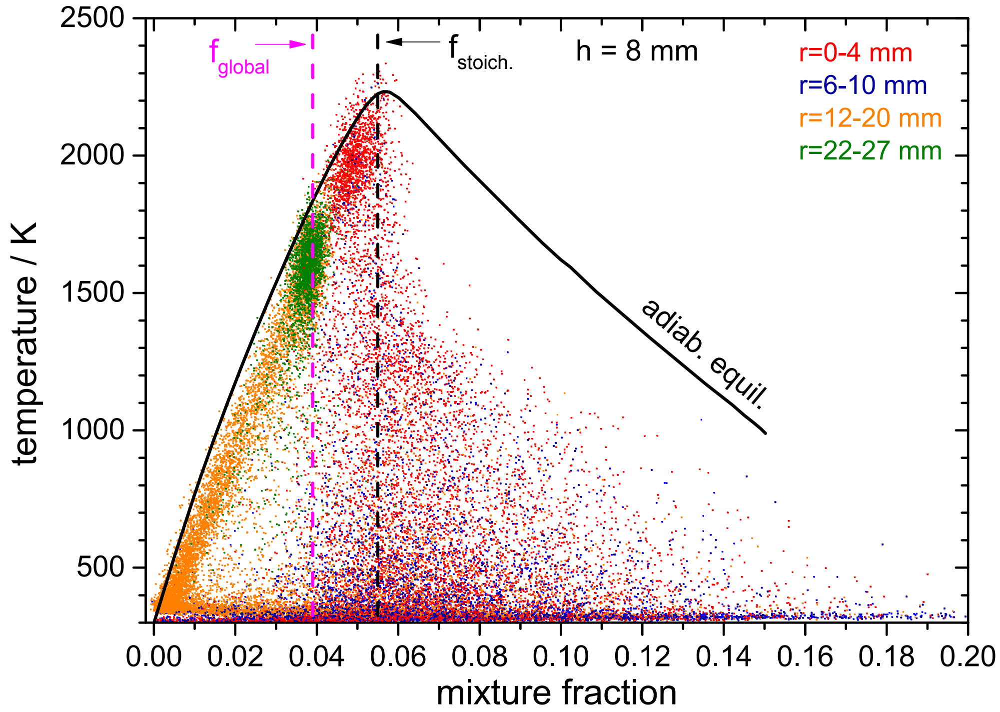
burner nozzle with swirler

Correlation between temperature and mixture fraction

500 single-shot Raman measurements at each radial location

measurements along radius at h=8 mm





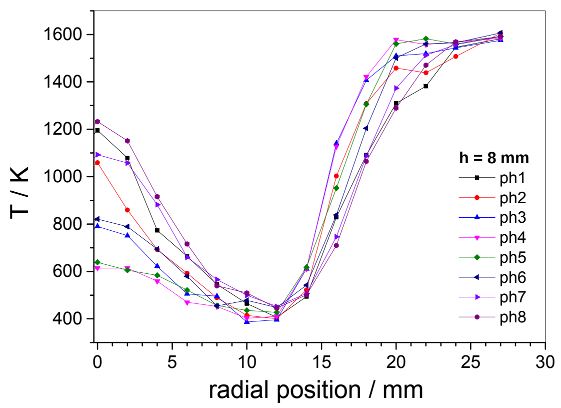
mixture fraction = (mass of fuel) / (total mass)

Large variation of composition and temperature

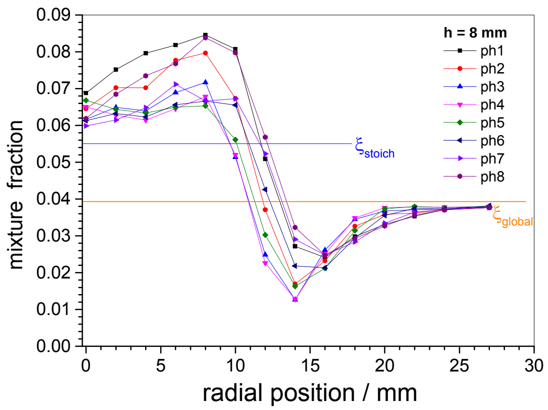
Radial profiles at h=8 mm in oscillating flame

- Thermo-acoustic oscillation at frequency of 400 Hz
- Phase-averaged mean values for 8 different phase angles

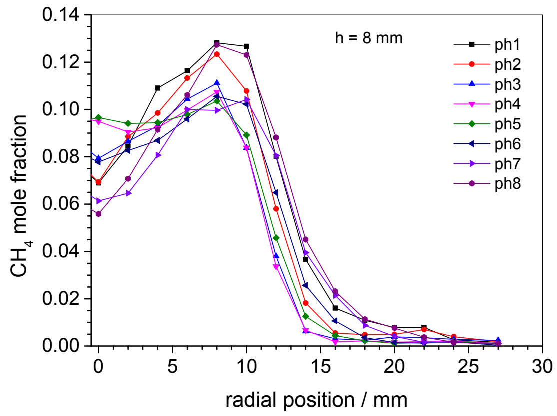
Temperature



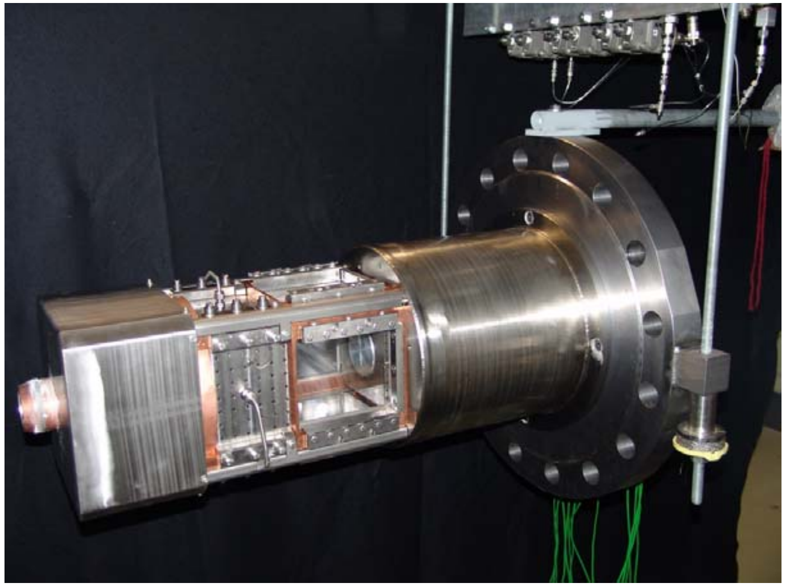
Mixture Fraction



CH_4 Mole Fraction



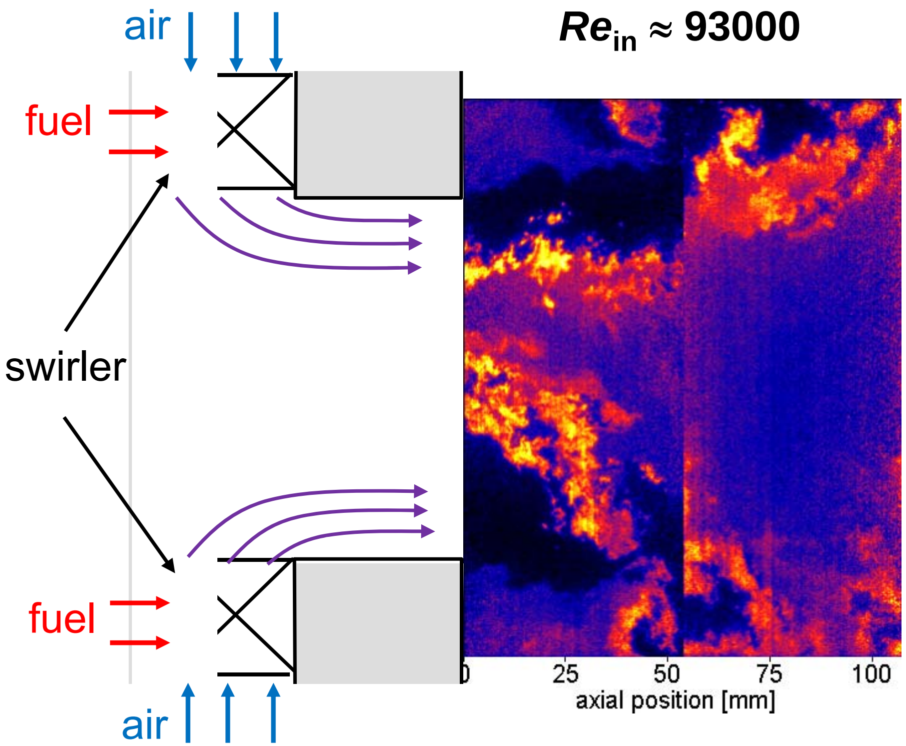
Raman measurements in high-pressure test rig
Industrial gas turbine burner installed in DLR optical test rig



- Premixed natural gas and air
- pressure up to 6 bar, Power = 0.335 – 1.08 MW, T_{air} = 670 K

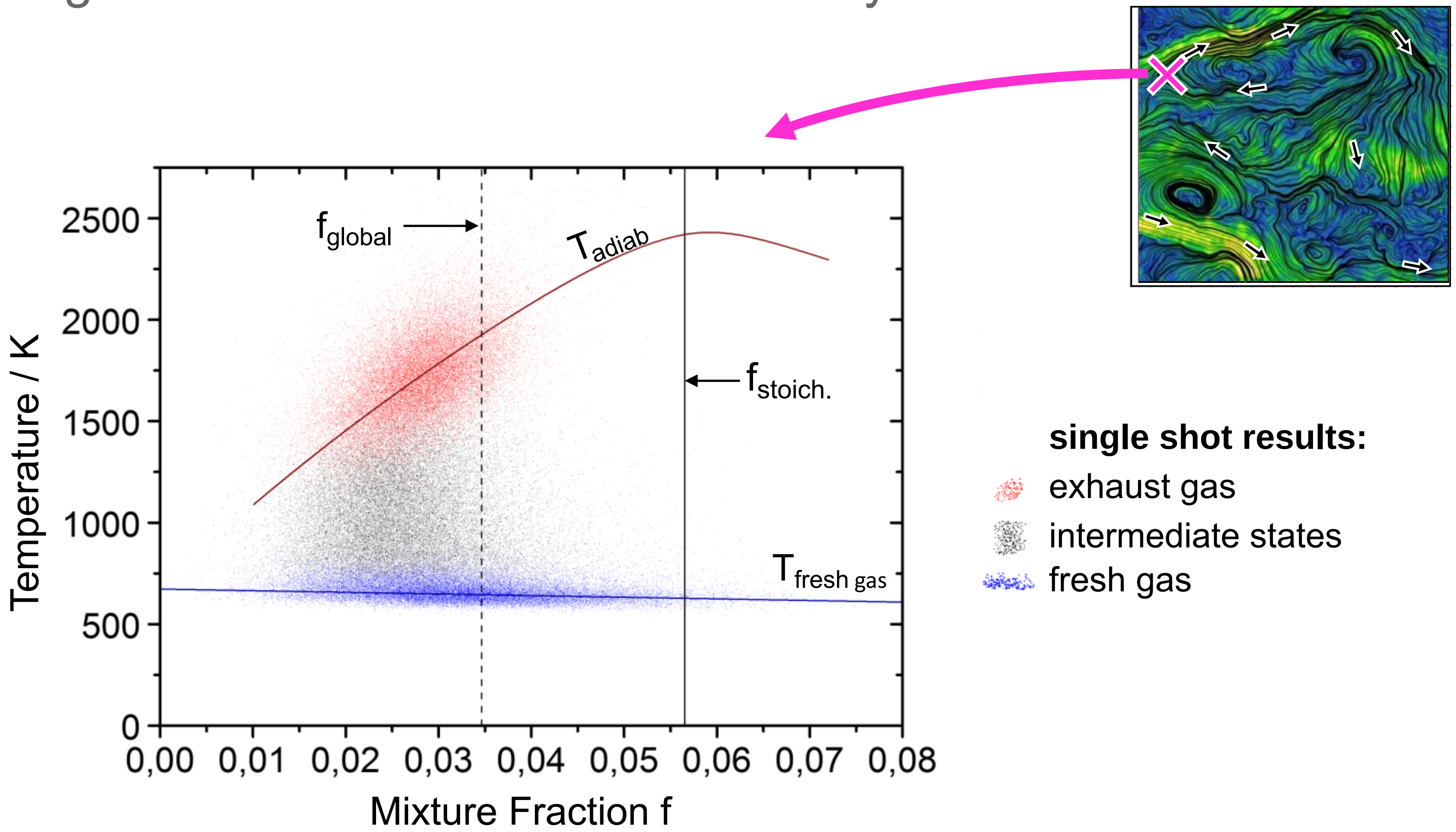
Flame structures from OH-PLIF measurements

Siemens G30 DLE swirl burner from SGT-100 turbine



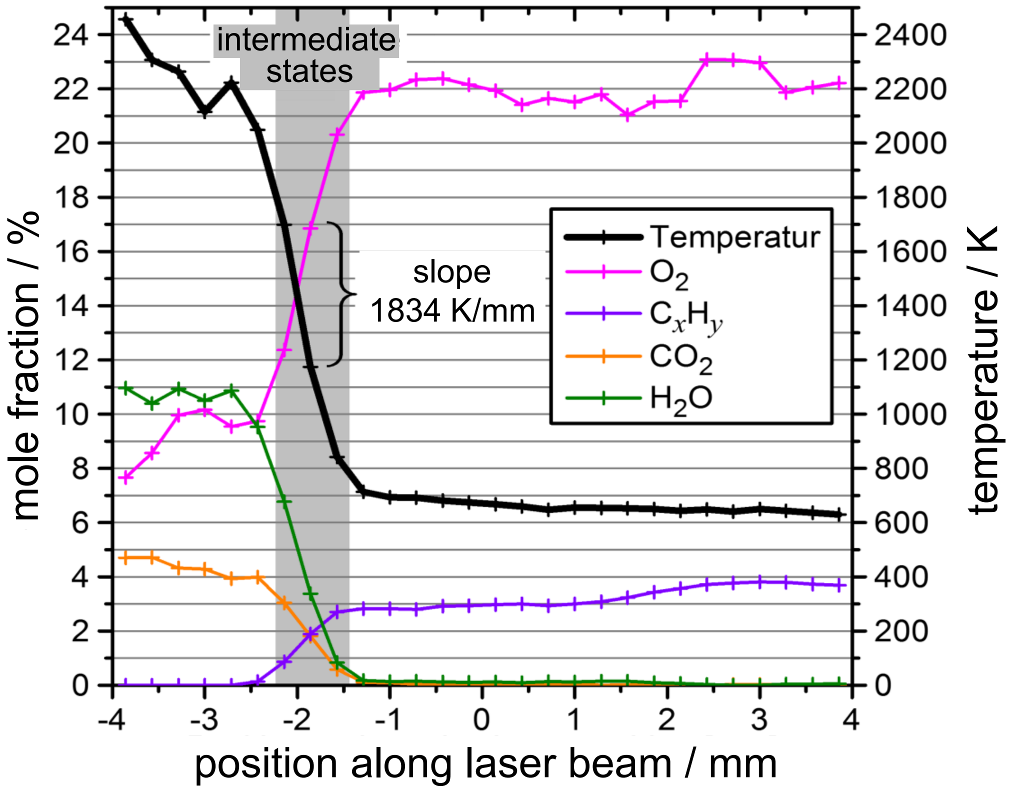
Scatterplot of temperature vs. mixture fraction

Single shot results from inner shear layer



Instantaneous profiles of temperature and species

From single-shot 1D Raman measurement



Profile with large gradients → indication of flame front

Conclusions

- Single-shot laser Raman scattering is an established technique for combustion diagnostics.
- Difficulties arise from small scattering cross section: Need of high laser pulse energy; signal interferences in flames with liquid fuels.
- Calibration measurements needed.
- Improvement of accuracy desirable.
- Advantages: Simultaneous line (1D) measurement of temperature and species concentrations yields huge amount of information about thermo-chemical state of flames.

Thank you for your attention

Backup

Challenges for laser Raman measurements in high-pressure test rigs

- Limited optical access, laser beams and signals must pass several windows.
- Window degradation by high thermal loads.
- Beam degradation and steering.
- Depolarization in windows by stress-induced birefringence.
- Non-traversable rigs → measurement technique must be traversed.
- Costs.