Laser Diagnostics for High-Pressure Gas Turbine Combustion

Wolfgang Meier

German Aerospace Center (DLR), Institute of Combustion Technology, Stuttgart, Germany

Workshop on Techniques for High-Pressure Combustion

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Deutsches Zentrum
DLR für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

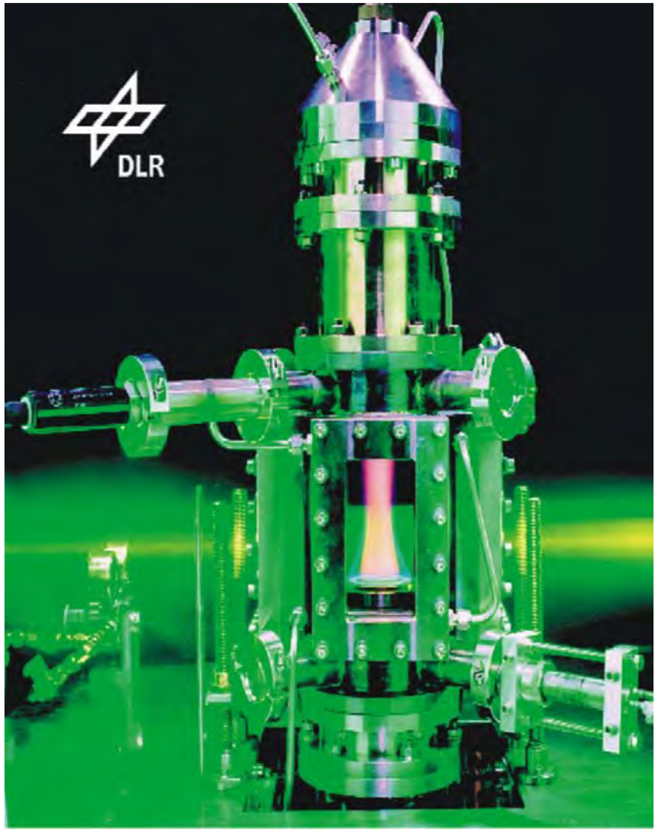
Outline

- Introduction to DLR Institute of Combustion Technology
- Measurement techniques and test rigs
- Problems encountered in high-pressure combustion
- Examples and results
- Summary and conclusions

Gas Turbine Combustion at DLR Stuttgart

Goals and research fields

- Reduction of Pollutants:
  NO_x, soot, UHC
- Instationary combustion phenomena:
  Ignition, re-ignition, extinction, thermo-acoustic
- Fuel-flexibility:
  Kerosene, natural gas of different quality, syngases, alternative fuels
- Burners and combustion systems:
  FLOX®, hybrid power plant



Laser Measuring Techniques for Different Quantities

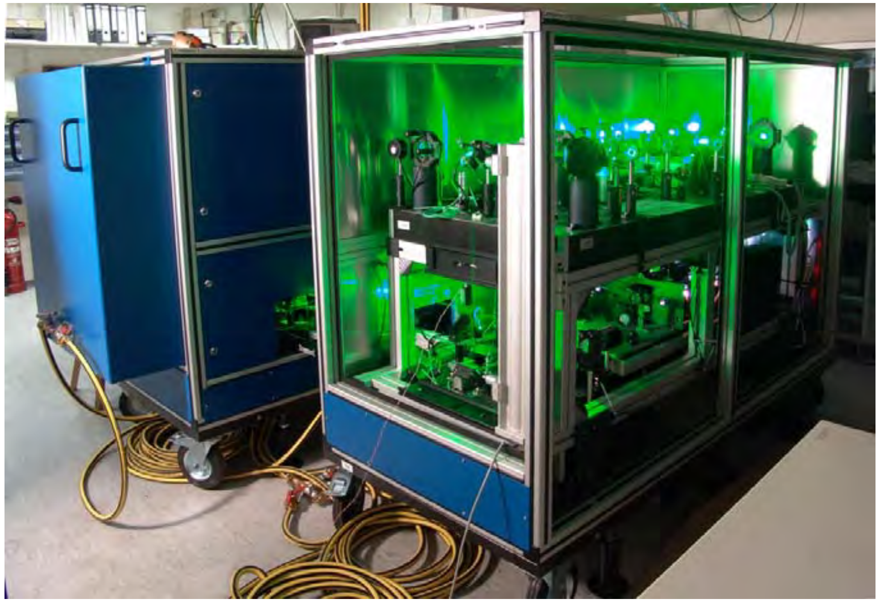
Quantity	Technique	Dim.
Flow field velocity	Particle Image Velocimetry (PIV)	2D
Species (OH, CH, NO, CH_2O, tracer), temperature, structures	Laser induced fluorescence (LIF)	2D
Major species, mixing, temp..	Laser Raman Scattering	0D or 1D
Temperature	Coherent anti-Stokes Raman scattering (CARS)	0D
Soot	Laser induced incandescence (LII)	2D
Atoms, Ions	Laser Induced Breakdown Spectroscopy (LIBS)	0D

All methods applied as single-pulse techniques with repetition rates up to 10 kHz

Mobile Laser Systems

- For measurement campaigns at test rigs, all over Europe.
- Installation in containers: temperature stabilized, compact.

CARS-Lasersystem

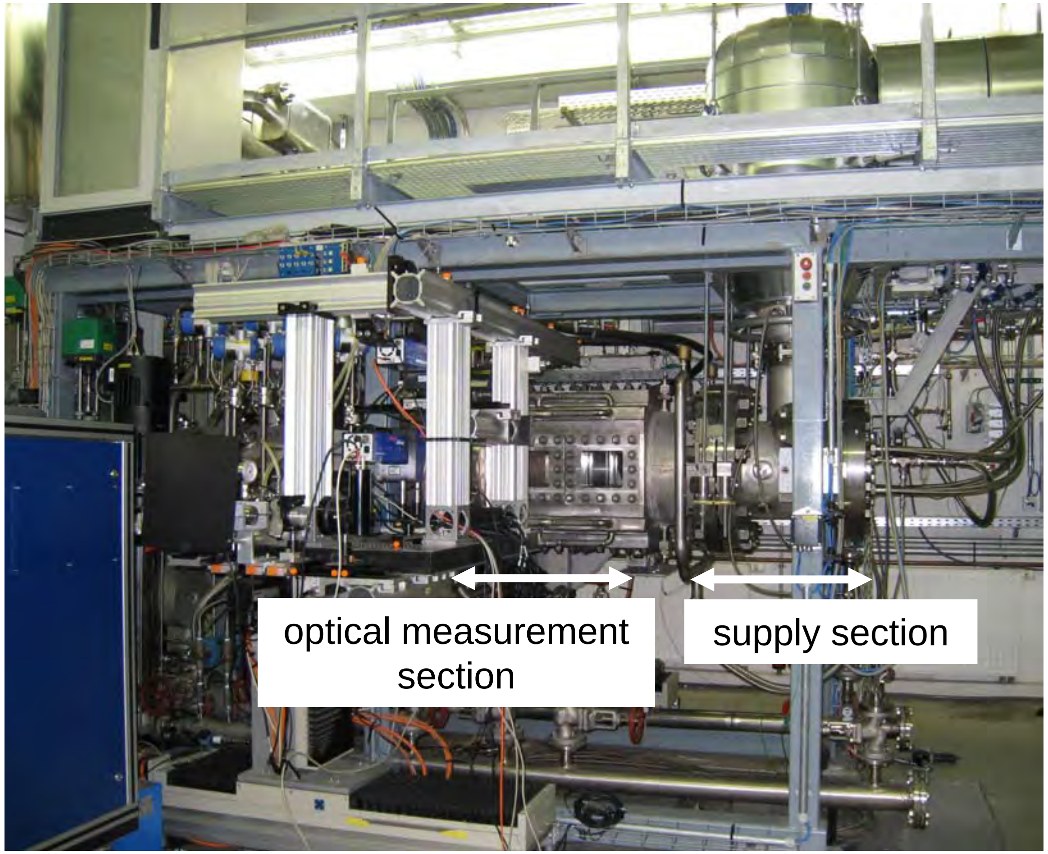


Raman-Lasers

High-Pressure Text Rigs

at DLR Stuttgart

High-Pressure Combustion Test Rig at Stuttgart



Air supply:

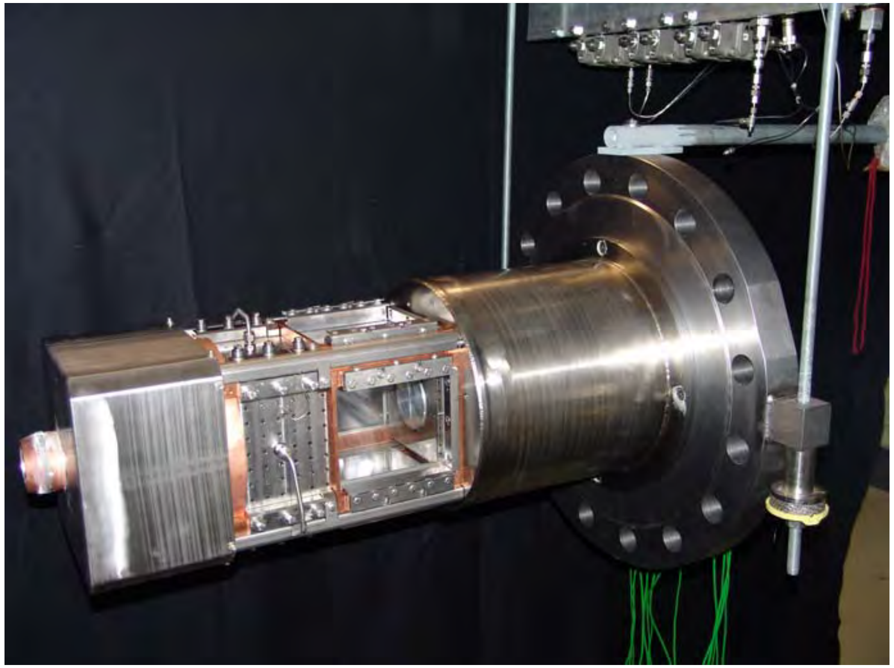
- Pressure: max. 40 bar
- Flow rate: max. 1.3 kg/s
- Inlet temperature: max. 1000 K

Gaseous and liquids fuels

Thermal power: max. 2 MW

Not traversable

High-Pressure Combustion Test Rig – Stuttgart



Typical combustion chamber
with optical access

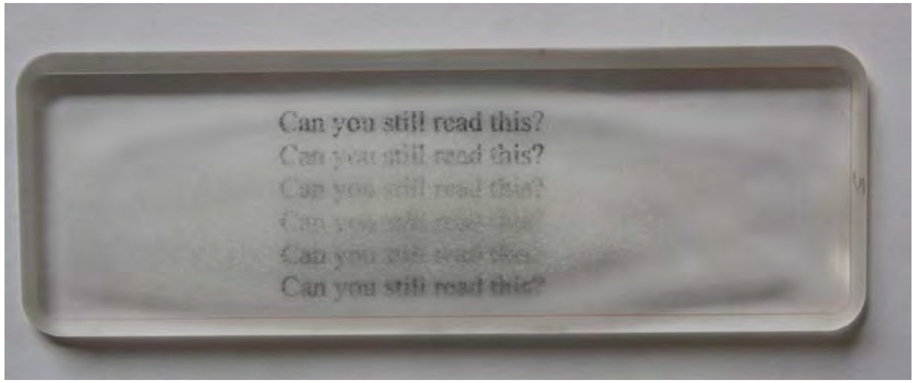
Example of a low-emission flame

Problems Encountered in High-Pressure Combustion

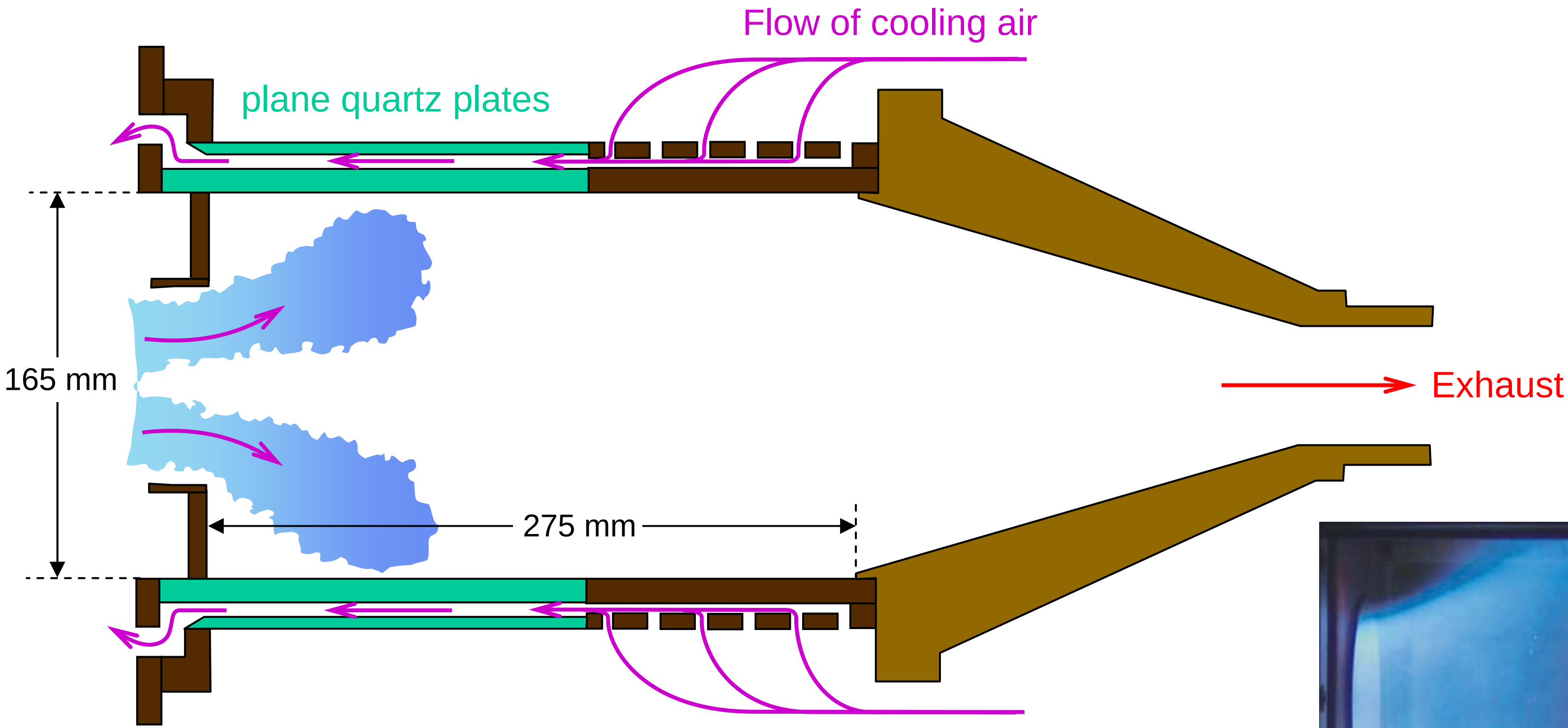
- Limited optical access, laser beams and signals must pass several windows.
- Window degradation by high thermal loads.
- Line broadening → signal reduction in LIF.
- Signal trapping (LIF, chemiluminescence imaging).
- Beam degradation and steering (CARS, Raman, LII).
- Depolarization in windows by stress-induced birefringence.
- Non-traversable combustors → measurement technique must be traversed.
- Costs.

Influence of Heat Load on Quartz Windows

Quartz window after extensive use at high pressure

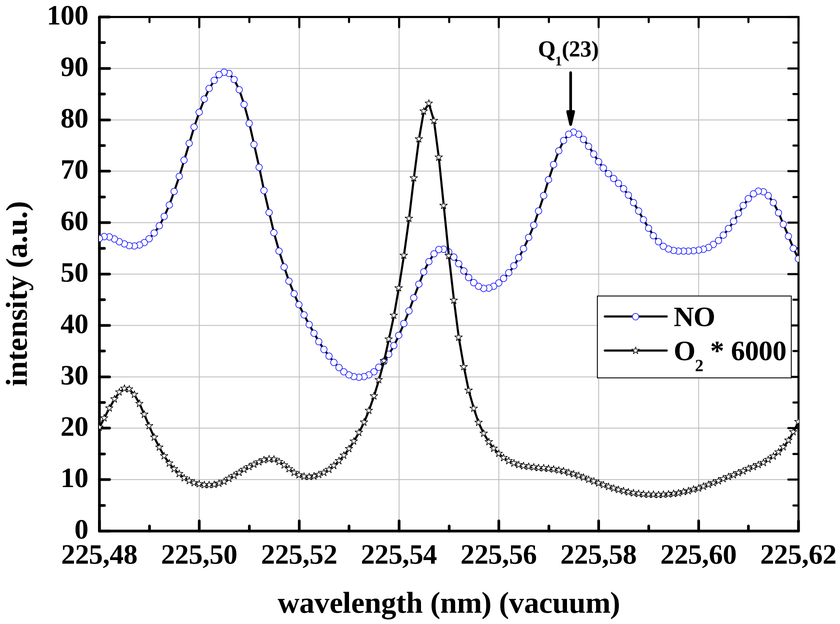


Window Cooling in Optical Combustion Chamber



LIF: Effect of Line Broadening

- NO was seeded as a tracer to the fuel or the combustion gases.
- LIF of NO A-X (γ bands at λ~226 nm) at 15 bar, T~1200 K.



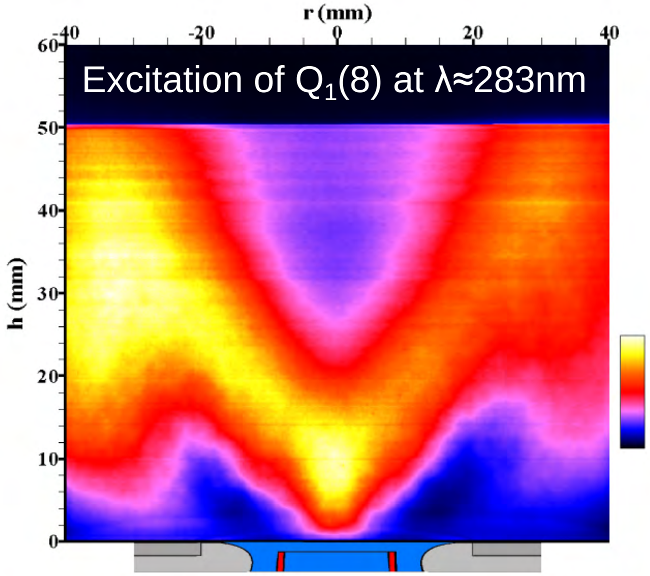
Sadanandan et al.,
Appl. Phys B 2011
DOI 10.1007/s00340-011-4655-4

- Lines not well resolved and broader than exciting laser radiation.
- Overlapp with (hot) O_2 spectrum (Schumann-Runge band).
- Different tracer available?

Absorption of Laser Radiation and LIF Signal

Excitation of OH in A-X (1,0) band in CH_4/air flames at 1 atm.

Averaged LIF signal from turb. flame at T≈1900 K



Absorption of laser from left to right ≈45%

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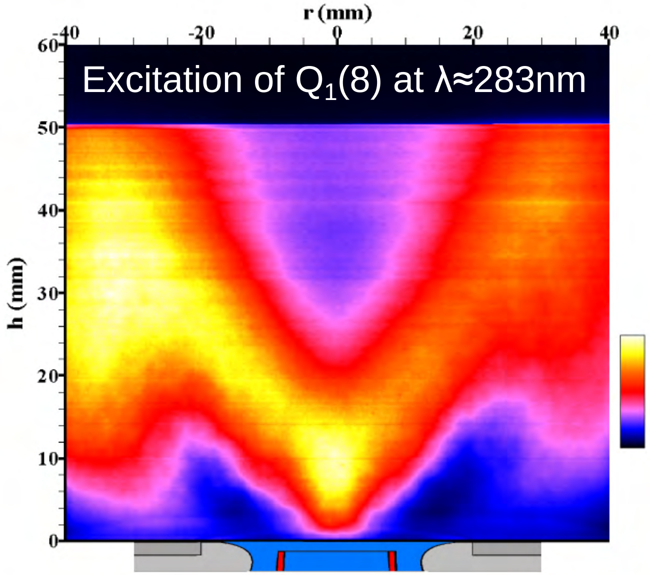

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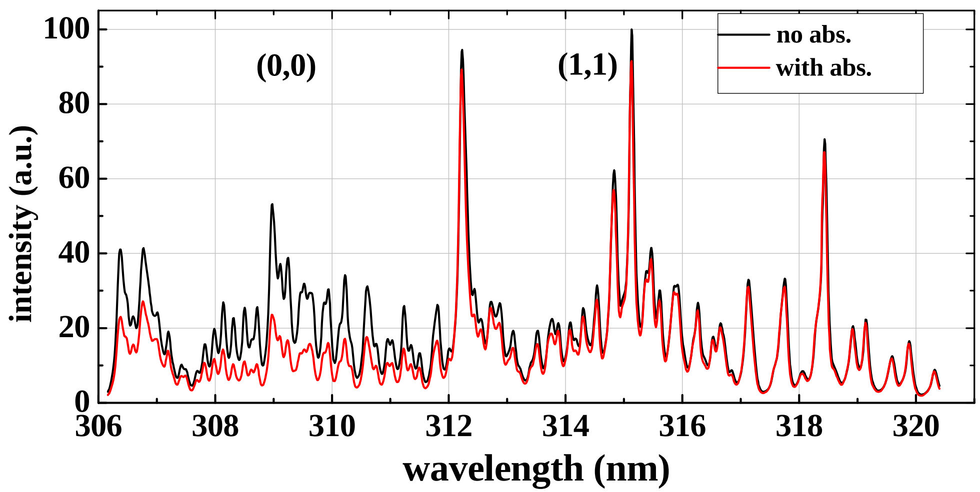
Emission spectrum after laser excitation



Absorption path: 54 mm through exhaust gas at T≈2100 K.

Sadanandan et al., Appl. Phys B 2011 accepted for publication

1D Laser Raman Scattering at the High-Pressure Rig

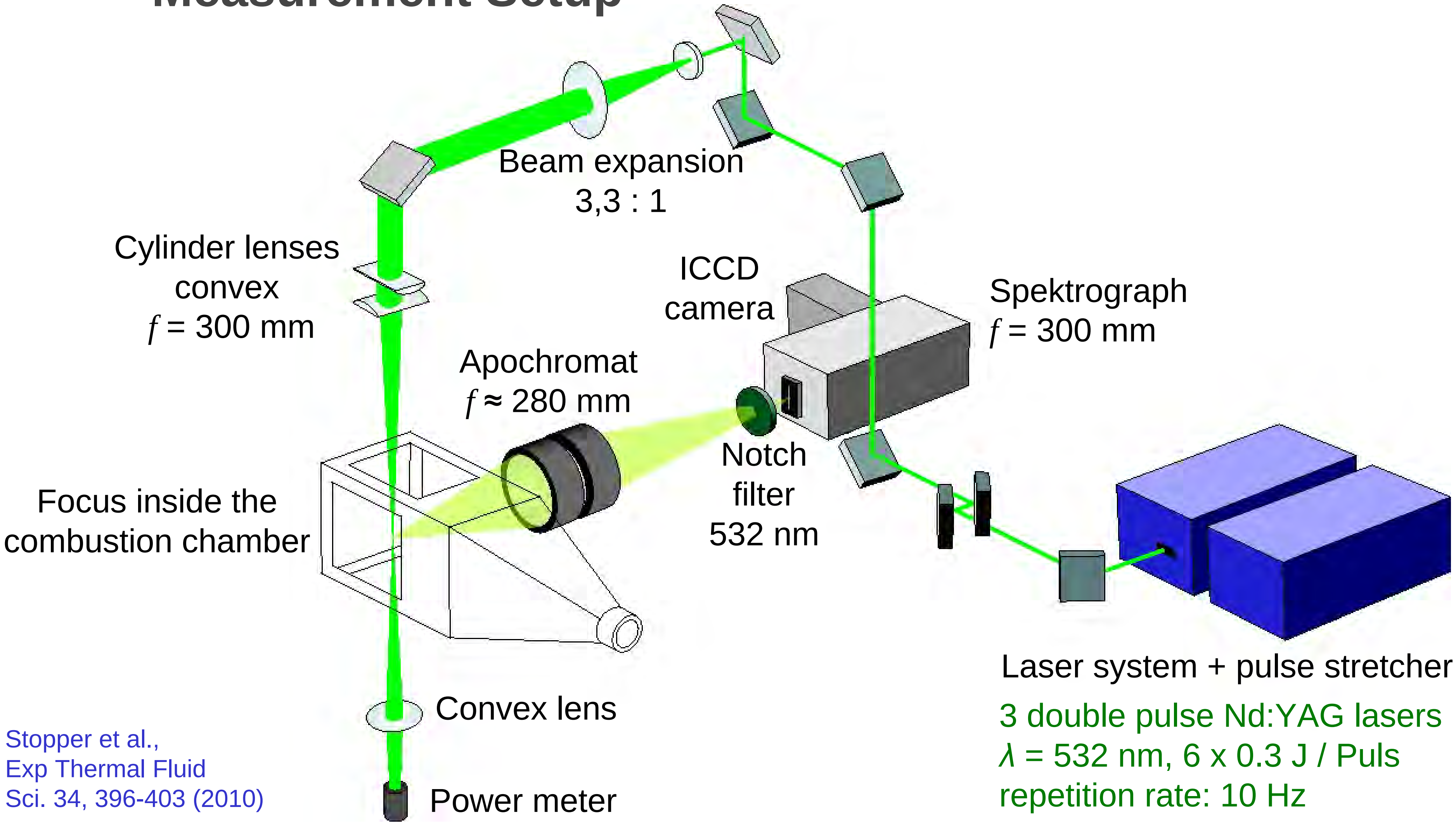
Goals

- Application to lean premixed GT combustors.
- Simultaneous single-shot measurement of major species concentrations, mixture fraction and temperature along a line.
- Identification of effects of unmixedness and finite-rate chemistry.
- Data for model validation.

Challenges

- Introduce high-power laser pulses with small beam waist into combustion chamber.
- Move laser and detection optics synchronously to change measurement position.
- Perform calibration measurements inside pressure housing.
- Cope with window contamination, alignment shifts, ….

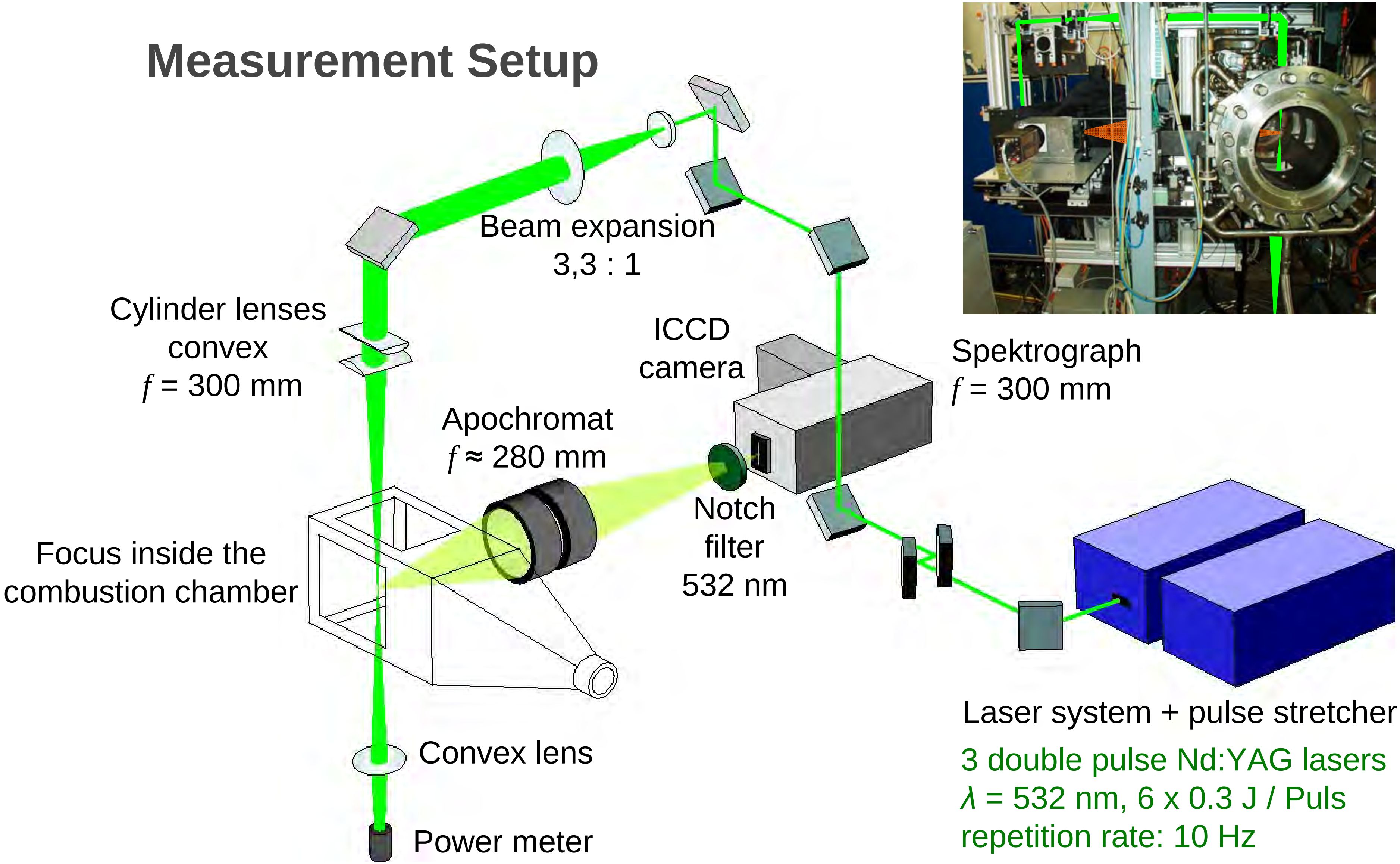
Measurement Setup



3 double pulse Nd:YAG lasers
λ = 532 nm, 6 x 0.3 J / Puls
repetition rate: 10 Hz

Stopper et al.,
Exp Thermal Fluid
Sci. 34, 396-403 (2010)

Measurement Setup



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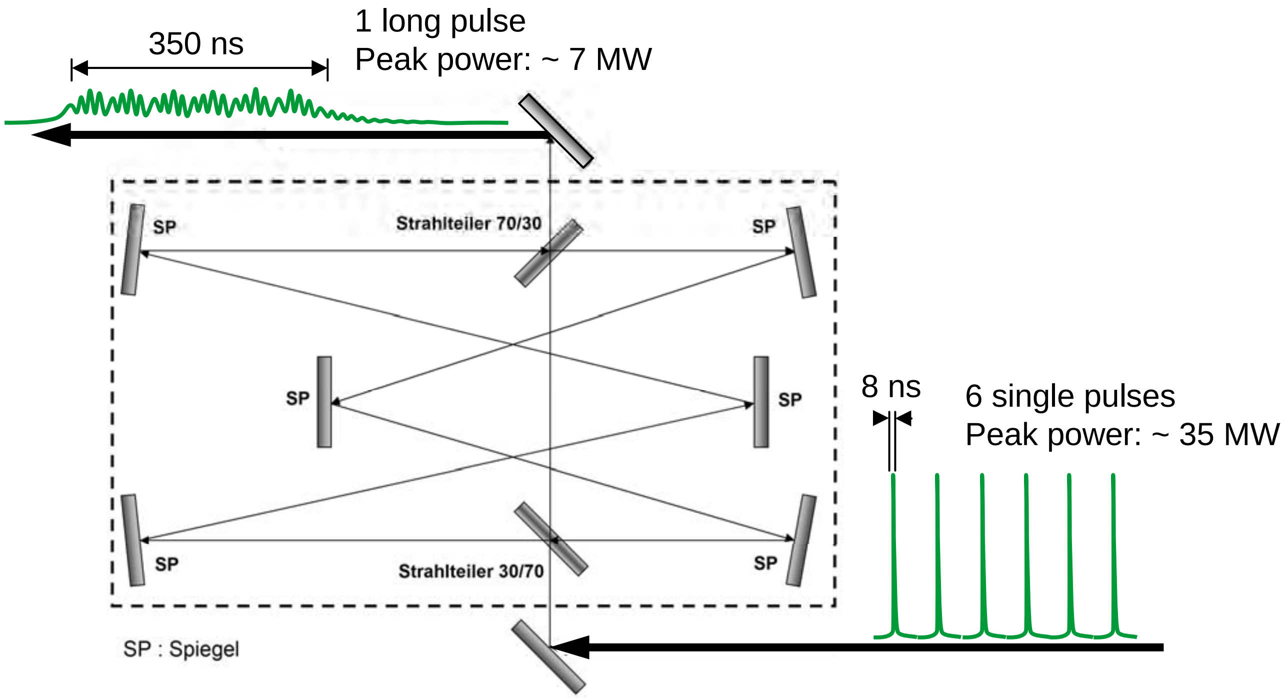
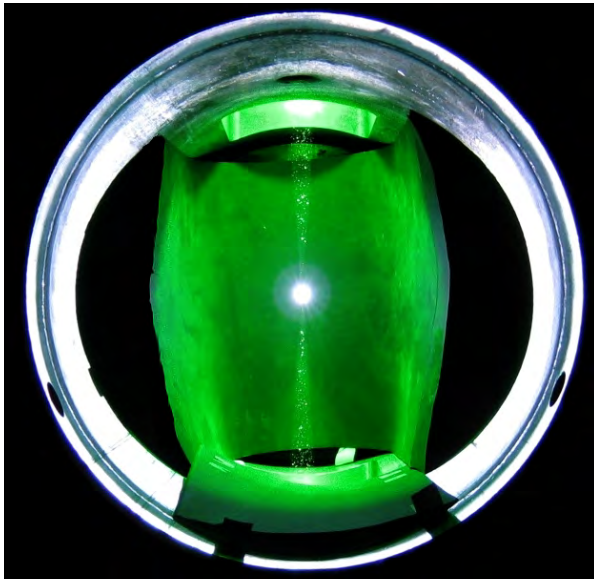
Pulse Stretcher for Laser Pulses



Beam is splitted by beam splitters and recombined after having travelled different distances.

Challenge

Optical breakdown in focus

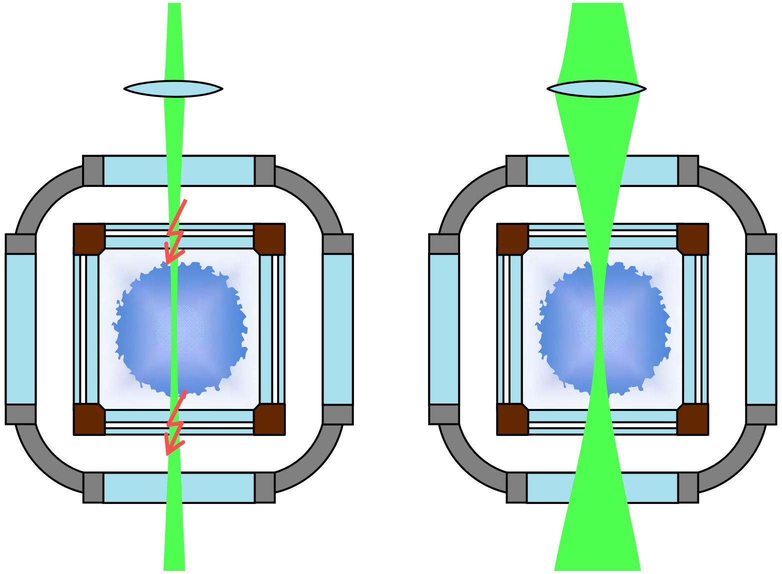


Reduced with small
beam divergence

$$\theta_{div} = \arctan\left(\frac{\lambda}{\pi \cdot w_0}\right)$$

➔ large beam waist

Damage of the combustor windows

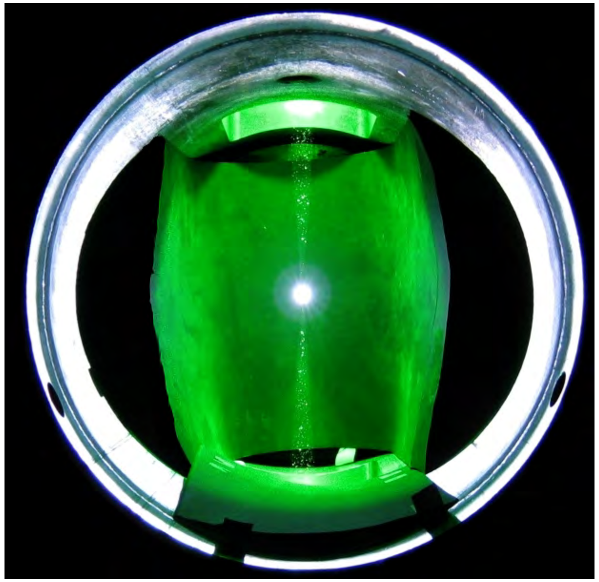


Requires large
beam divergence

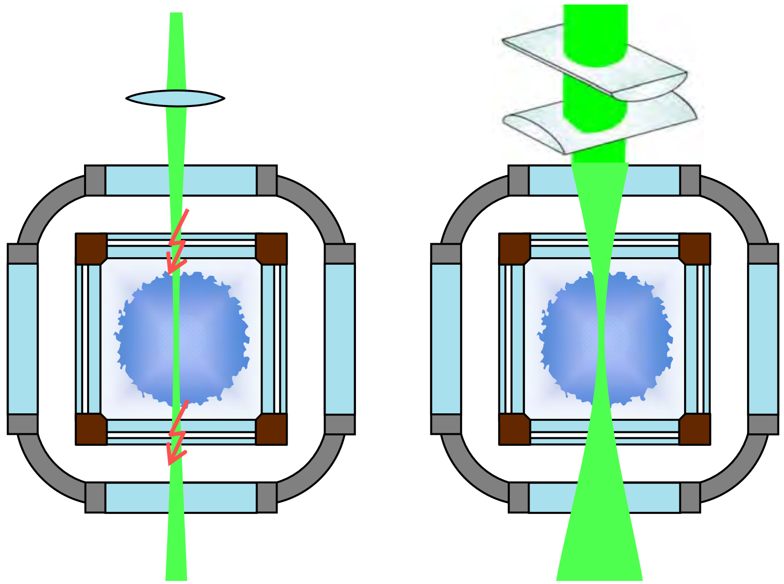
➔ large cross section on windows

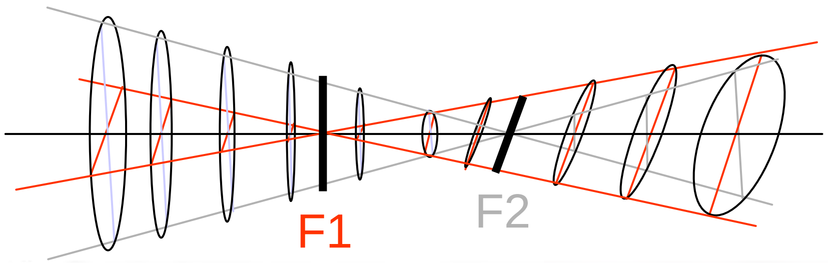
Our Approach: Generate Astigmatism

Use of 2 cylindrical lenses



astigmatic fosus



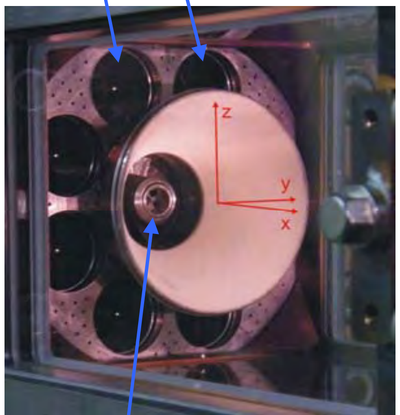


Beam waist about 0.5 mm

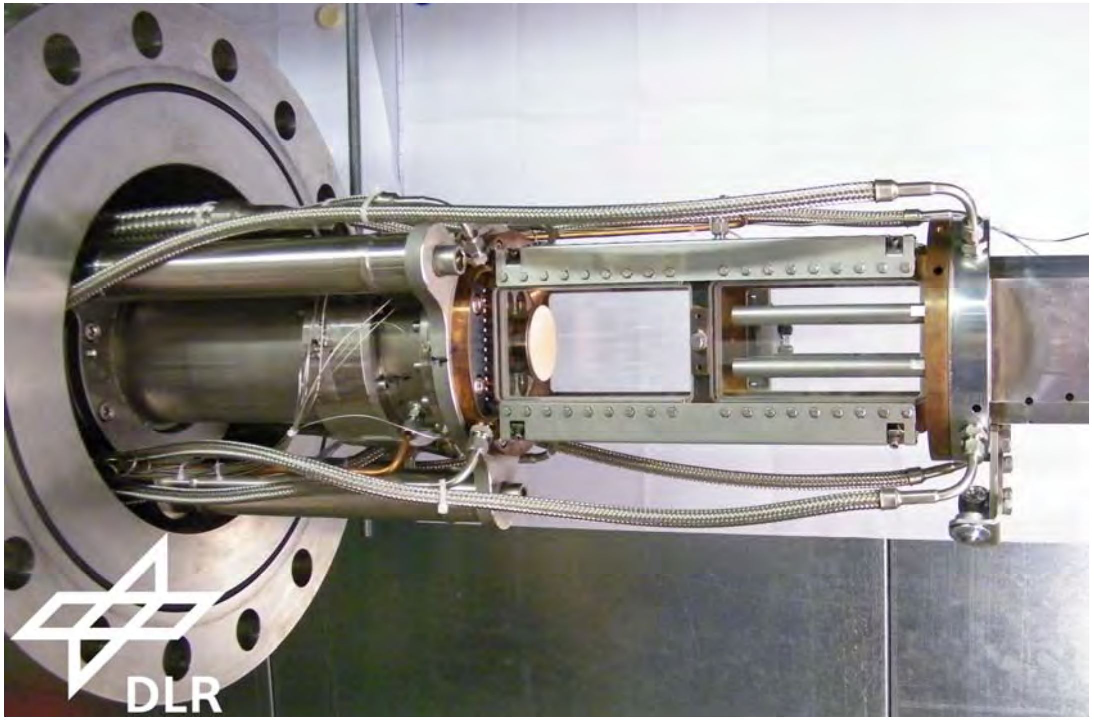
Raman Measurements in Scaled GT Combustor

- Lean premixed natural gas /air flames (p=4 bar, $P_{therm.}$=1.2 MW).
- Staged combustion: 1 pilot burner, 8 main burners.
- One goal: Interaction between pilot and main burners.

main burners

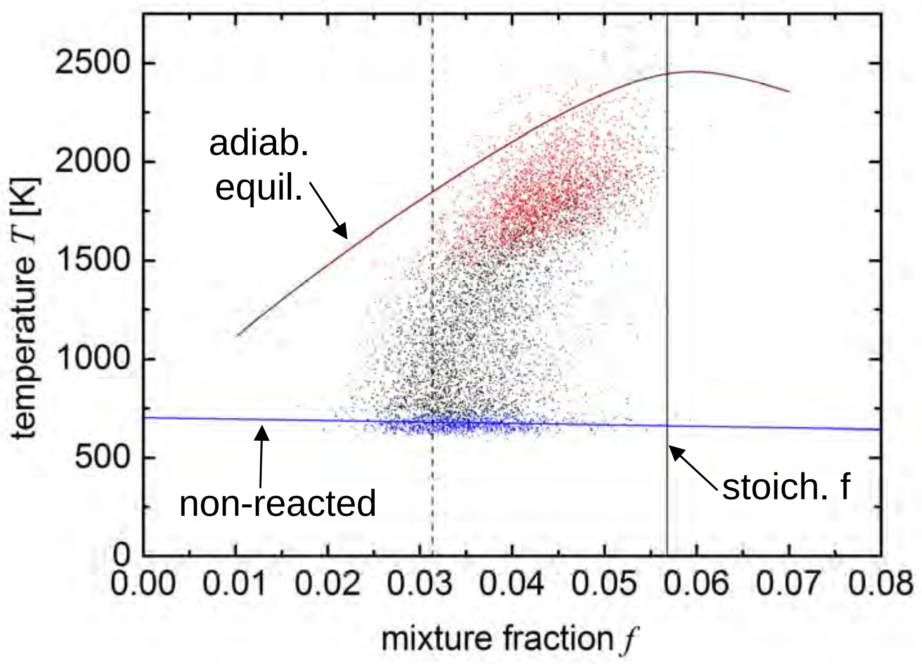


pilot burner



Lückerath et al., Proc. ASME Turbo Expo 2011, GT2011-45790

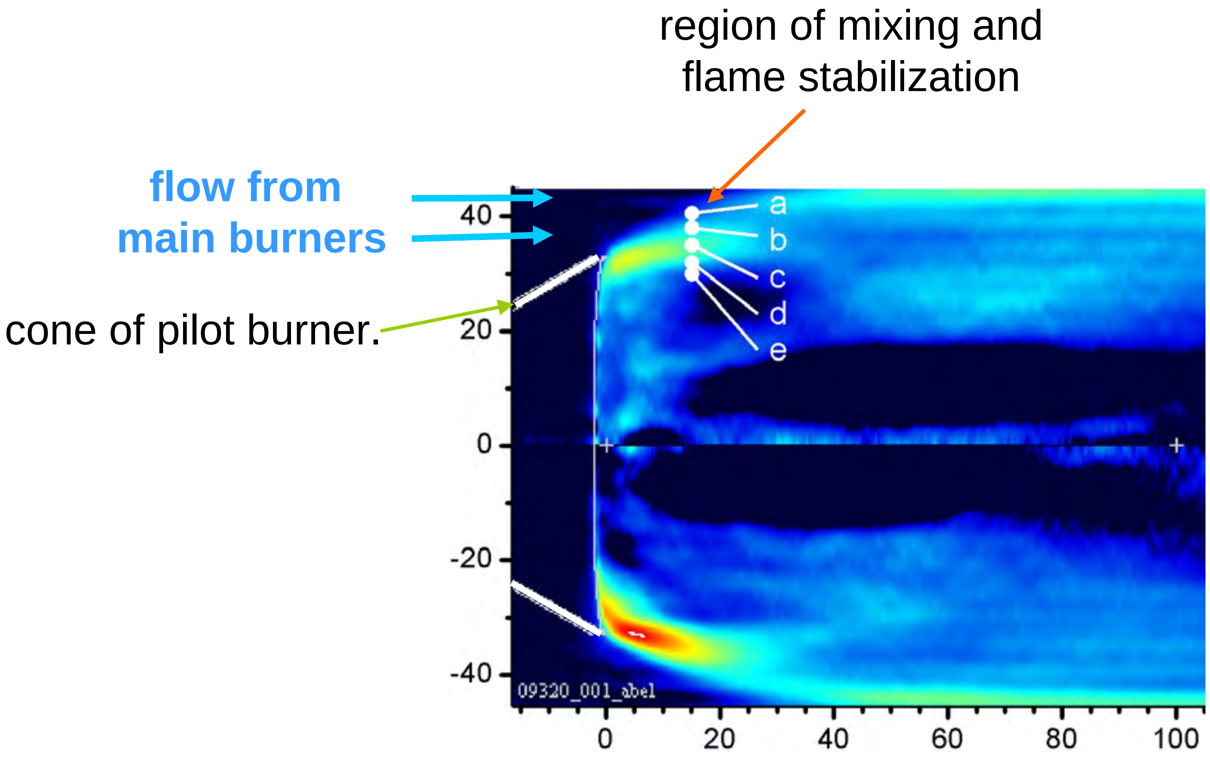
Scatterplot of Temperature vs. Mixture Fraction



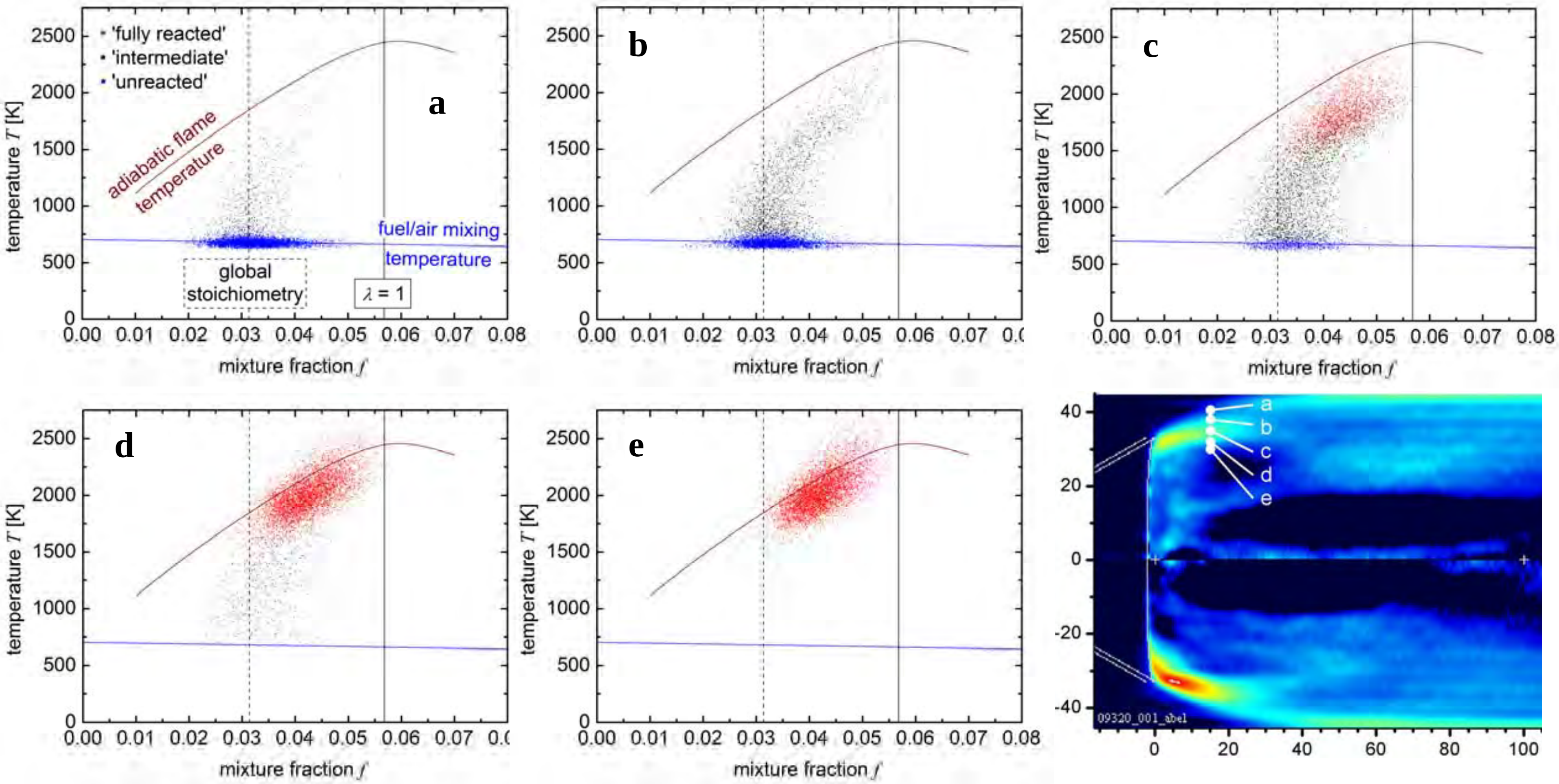
- Symbols represents results from single-shot measurements.
- Different states of mixing and reaction progress.

Flame Shape from Chemiluminescence

OH* chemiluminescence, Abel-transformed



Mixing and Reaction Progress



Wish List for Raman Measurements

- Laser with ~1 µs pulse duration, pulse energy >1 J, good beam profile, wavelength close to 400 nm.
- Detection camera with high quantum efficiency, low noise, gateable.
- Window material with better heat resistance or improved cooling concept.

Summary and Conclusions

- Laser measurements at high-pressure test rigs could be performed successfully.
- Window degradation is one of the most serious problems in our high-pressure combustion chambers.
- Effects of line broadening, beam steering, etc. reduce the quality of the results.
- Possible improvements: fs-CARS? Long pulse lasers for Raman?