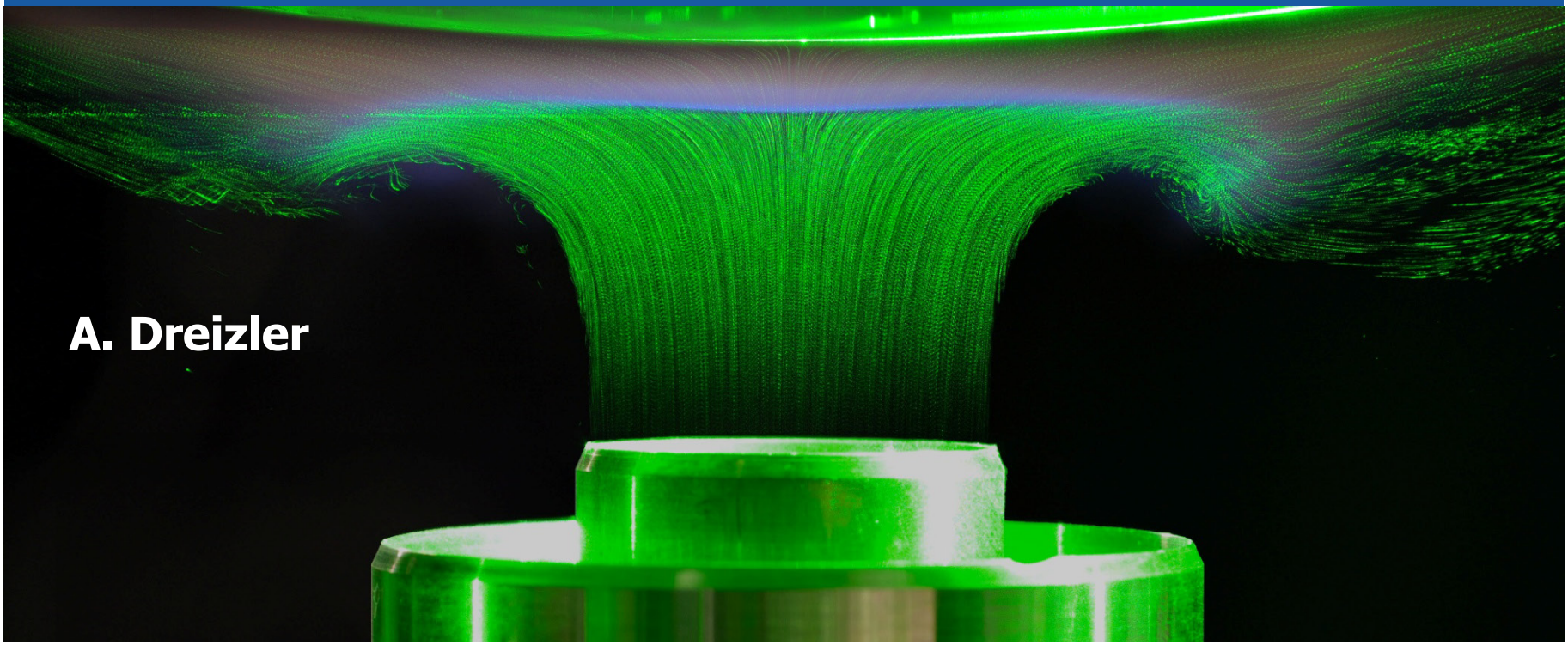
Advanced Laser Diagnostics in Combustion

TU Darmstadt, Germany
Dept. of Mechanical Engineering
Institute for Reactive Flows and Diagnostics



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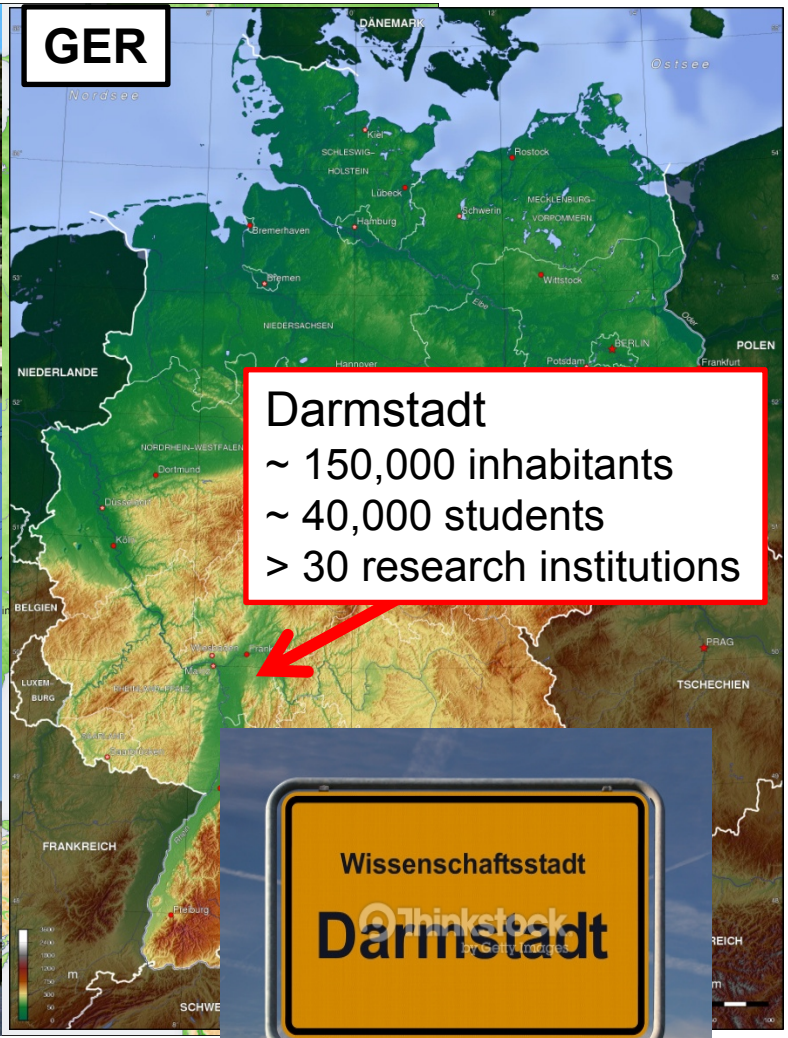
Where to find the city of Darmstadt?

TECHNISCHE UNIVERSITÄT DARMSTADT



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TU Darmstadt in numbers

TECHNISCHE UNIVERSITÄT DARMSTADT

Students	25,900
Professors	300
Research associates	2,150
Administrative and technical employees	1,750

One focus: “energy conversion“

Engineering	50%
Natural Sciences	35%
Social Sciences	15%

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TU Darmstadt: Dept. of Mechanical Engineering

TECHNISCHE UNIVERSITÄT DARMSTADT

Students	3,000
Professors/institutes	27
Research associates	>400
Third party funding (2015)	46 Mio €

Institute Reactive Flows and Diagnostics
http://www.rsm.tu-darmstadt.de/rsm/index.en.jsp

- Prof. Dreizler (director)
- Dr. Böhm, Dr. Wagner, Prof. Ebert
- 25 Research associates (ph.D.)
- 9 technical and administrative staff
- Third party funding in 2015 >3 Mio €

→ **Focus on Turbulent Combustion**
→ **Advanced Laser Diagnostics**

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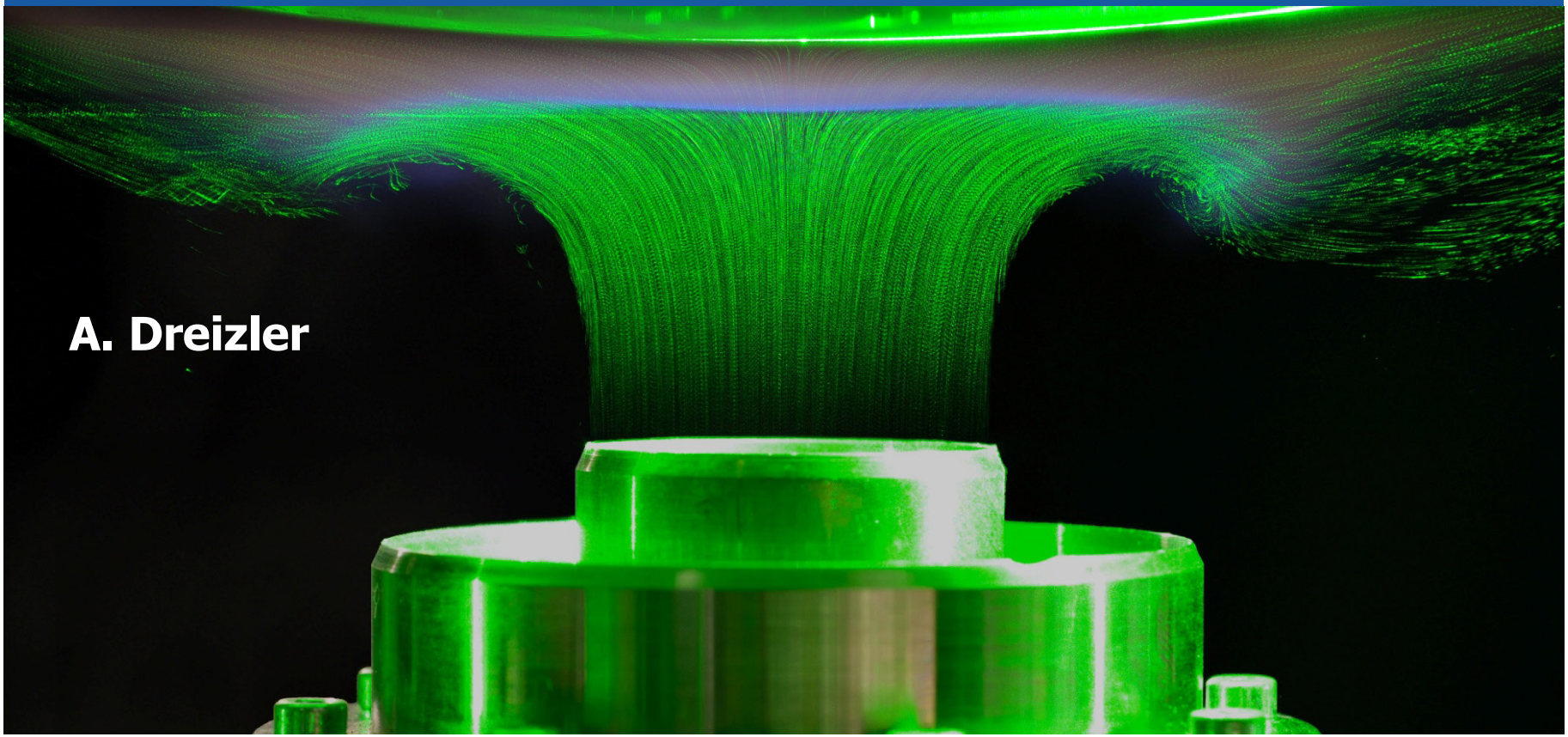

Challenges in combustion research

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→ Need for efficient, clean and flexible combustion technology

→ Coherent action of combustion-community: experiments, theory/modeling and simulation

→ Objective of this lecture series:

- Highlight role of combustion diagnostics
- Provide some basics of light – matter interaction
- Discussion of most important laser combustion diagnostic methods
- Present some topical application examples

Content

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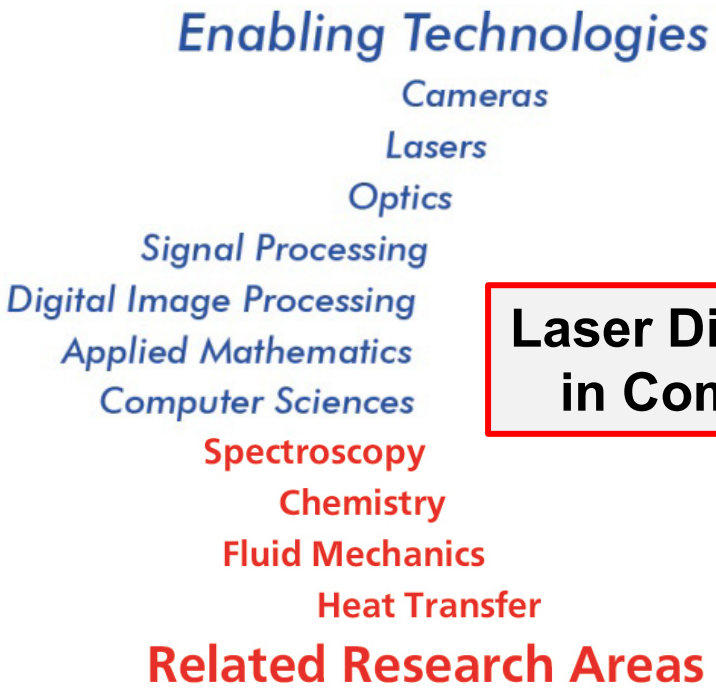
- Introduction
- Benchmark experiments
- General requirements for laser combustion diagnostics
- Particle-based velocimetry
- Gas-phase thermometry
- Surface thermometry
- Gas-phase concentration measurements
- Towards 4D-imaging
- Application examples
  - Flame-wall interactions in canonical configurations
  - Effusion cooling in gas turbine combustor
  - IC Engine: Technology development

Introduction
Laser diagnostics: contributions and context



Laser Diagnostics in Combustion

Combustion System Tasks:
1. Phenomena
2. Validation data
3. Technology develop.
4. Robust sensing

Quantities of primary interest in combustion

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- **Flow field**
  - Mean velocities, fluctuations, Reynold-stresses
  - Strain, dilatation, vorticity
  - Integral length and time scales
  - Power spectral densities
- **Scalar field**
  - Means and fluctuation of temperature and chemical species concentrations
  - Structural information based on 2D- or quasi 3D-diagnostics
  - Scalar gradients
  - Wall/ nozzle temperatures
- **Inflow** conditions, boundary conditions
- Information on **unsteadiness**, temporal sequences of flow/ scalar fields

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Using light – matter interaction for diagnostics

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Methods from physics

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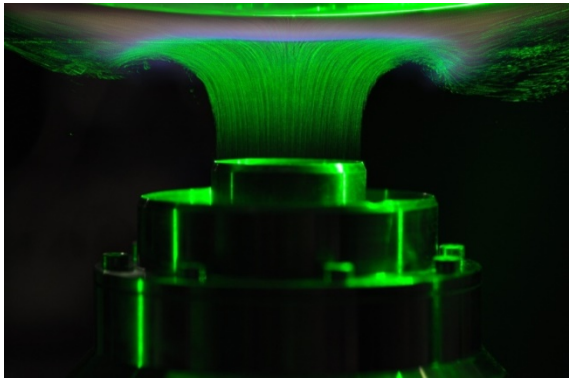
Engineering sciences

Transfer of methods

- Measuring by laser light
- Insitu-diagnostics → measuring inside combustors
- Non- or minimal intrusive
- High temporal resolution (~10^{-8}s)
- Reasonable spatial resolution (>10µm)



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Laser diagnostic methods

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- Flow field
  - Laser Doppler Velocimetry (LDV), 1 to 3 components
  - Particle Image Velocimetry (10 Hz – 30 kHz)
    - 2 dimensional and 2 components (2D2C)
    - 2 dimensional and 3 components (2D3C – stereo PIV)
    - 3 dimensional and 3 components (3D3C – tomographic PIV)
- Two-phase flows
  - Mie scattering
  - Phase Doppler Anemometry (PDA)
- Scalar field
  - Mie scattering
  - Laser absorption spectroscopy (LAS) – but line-of-sight
  - Planar Laser-Induced Fluorescence (PLIF)
  - 1D Raman/Rayleigh scattering
  - Coherent anti-Stokes Raman Spectroscopy (CARS)
  - Thermographic Phosphors (TG)

Towards complex combustion systems

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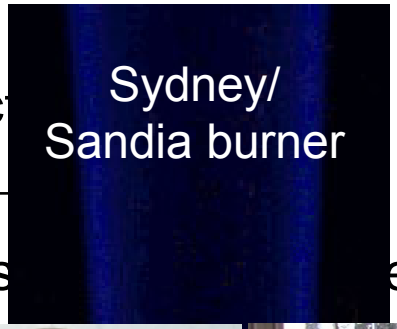
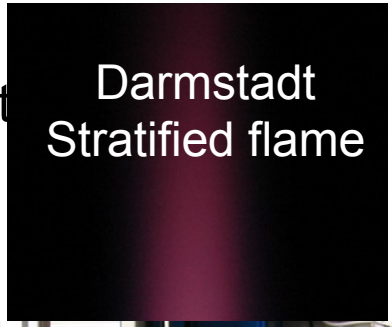
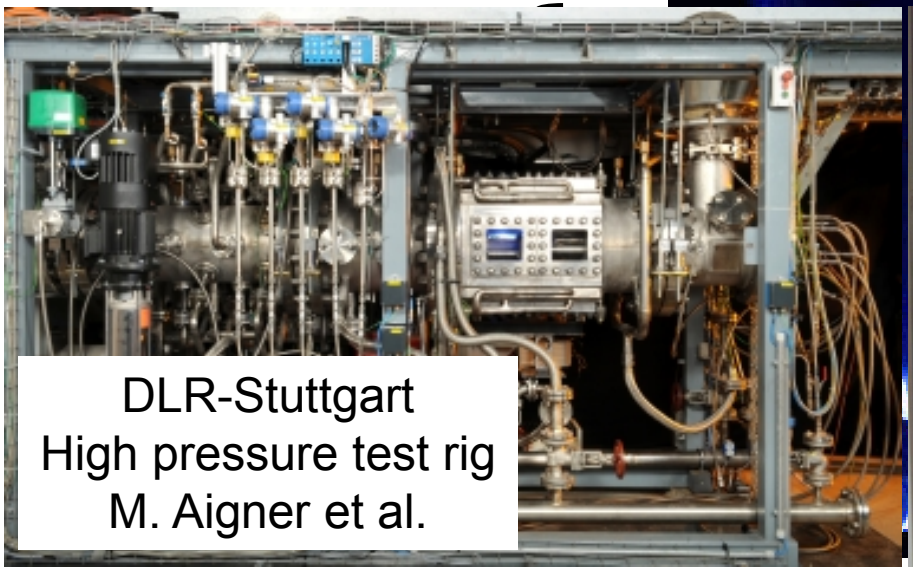
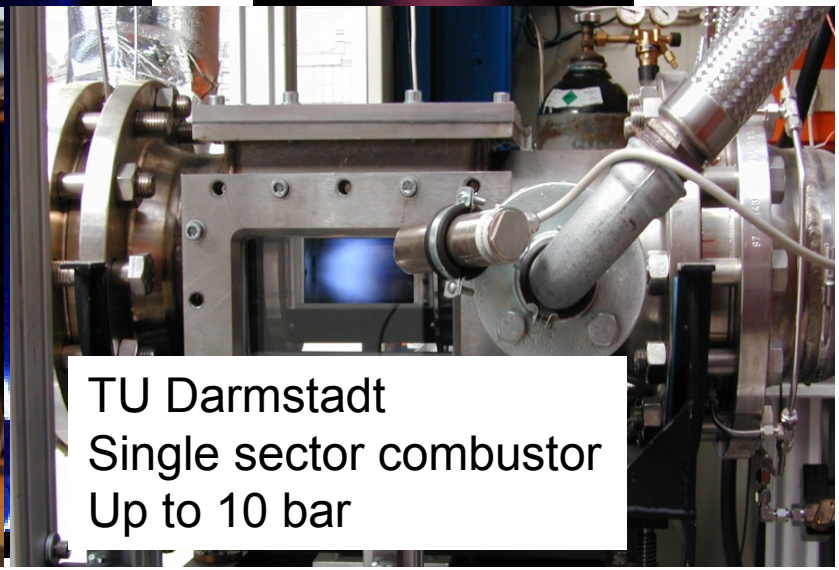
- Laser diagnostic methods have been used primarily in unconfined gaseous flames
- Additional challenges in prac syst
  - Enclosure, high pressure –
  - High turbulence levels → s es







DLR-Stuttgart
High pressure test rig
M. Aigner et al.



TU Darmstadt
Single sector combustor
Up to 10 bar

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Task 1: Studying phenomena by laser diagnostics

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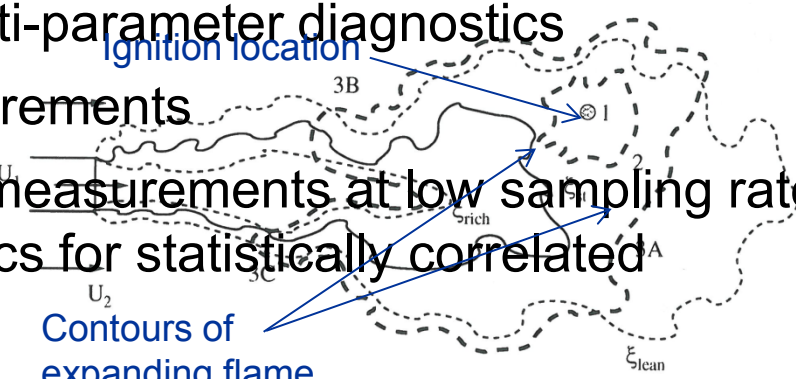
- Mimic specific properties of practical combustion systems in canonical configurations
- Adapt/develop laser diagnostics for monitoring of a specific property
- Exploit rapid developments in laser and camera technology to break new ground
  - From single-parameter to multi-parameter diagnostics
  - From 0-D towards 3-D measurements
  - From statistical independent measurements at low sampling rates towards high-speed diagnostics for statistically correlated measurements

BOSCH

Flame propagation in stratified mixtures



E. **Mastorakos**, PECS 2009: Schematic of flame kernel expansion following local ignition

→ Ultimate goal: summarize phenomenological understanding in physically consistent and predictive mathematical models

UNIVERSITY OF CAMBRIDGE

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Task 2: Provide validation data

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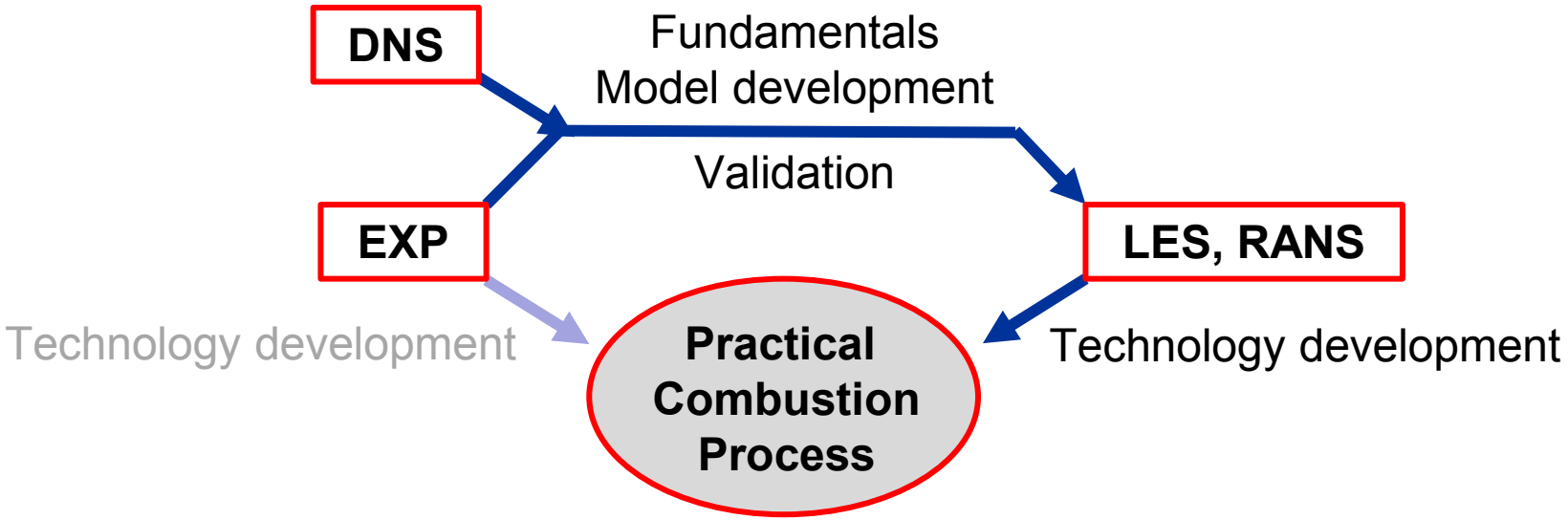
- Interplay of experimental and numerical methods for developing future combustion technologies



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Task 2: Provide validation data

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- Validation sequence: from simple to complex
  - Stepwise approach: select specific sub-processes and build experiment to develop and validate models for this specific sub-process
  - Example:
    - Turbulence-chemistry interaction
    - Soot formation
    - Spray breakup
    - …

Task 2: Provide validation data - from simple to complex, strategy at TUD

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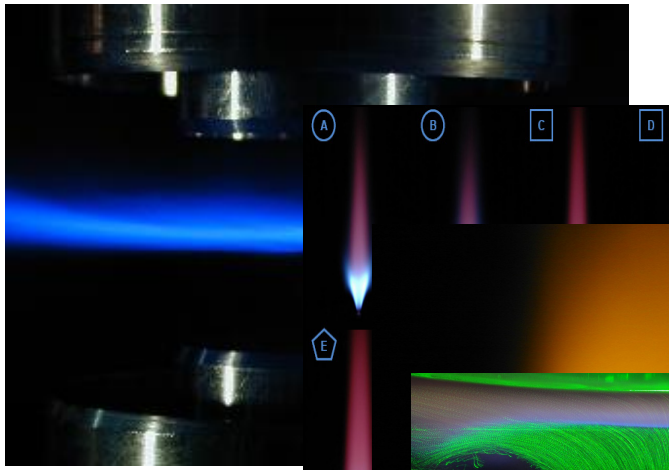
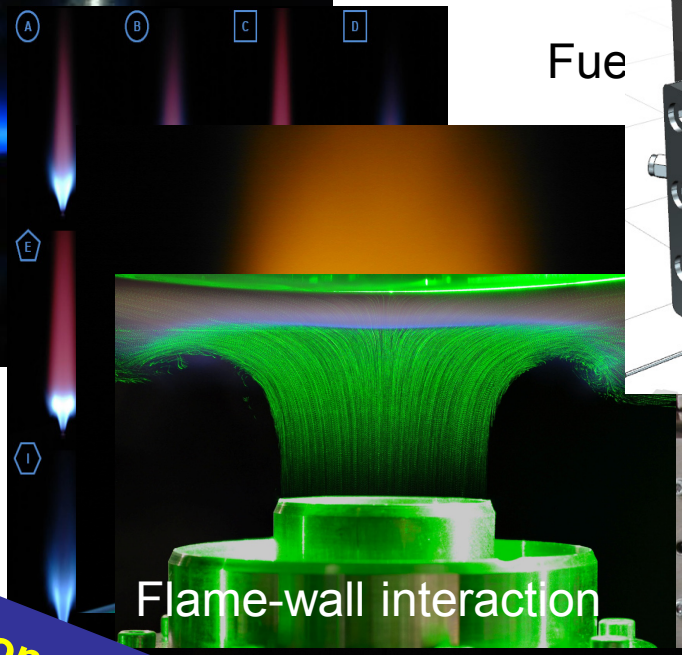
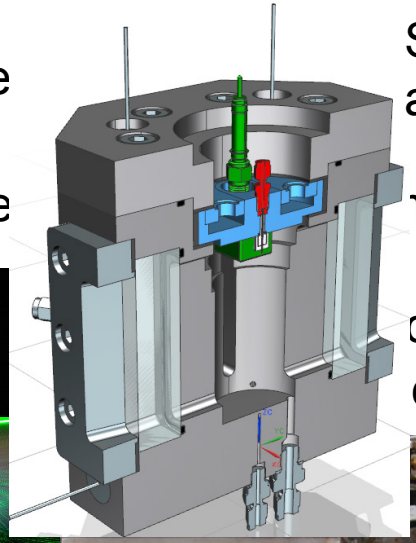




Turbule

Fue

Flame-wall interaction



Supercritical droplets and droplet combustion

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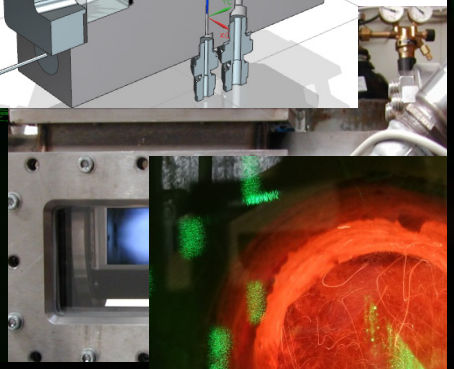
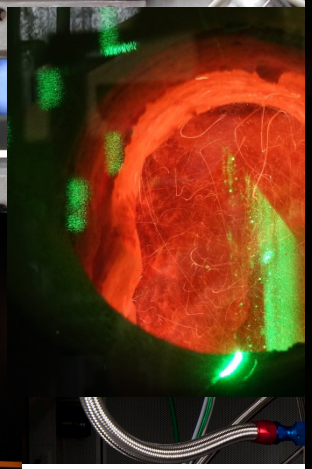
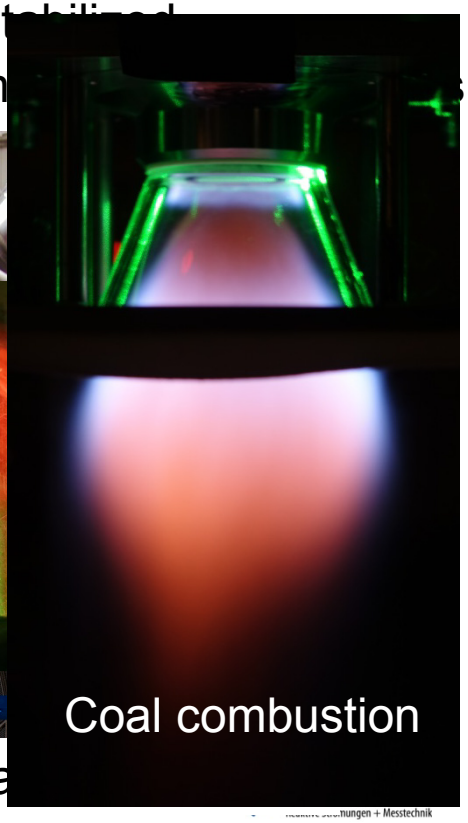
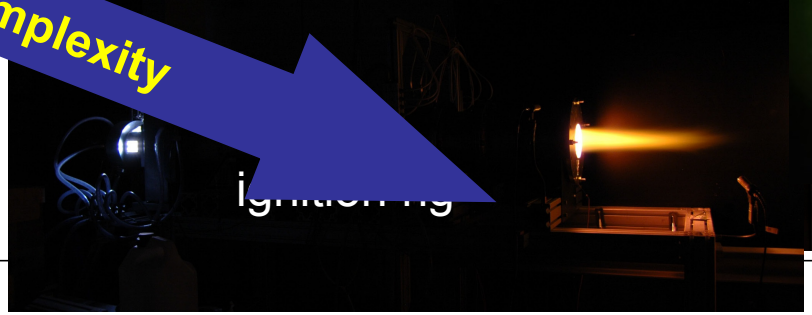






Coal combustion

Complexity



ignition rig

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Task 3: Support technology development

- Development of future combustion technology requires billions of Euro (IC engine, gas turbine combustor, coal power plant, rocket motor, …)

→ Not the core-business of universities

- University task: development of methods (experimental, theoretical, numerical) supporting technology development and educate well-trained engineers

→ In this context: Transfer of measurement methods to industry

  - By graduated students
  - Bilateral industry projects

Task 4: Develop robust sensors

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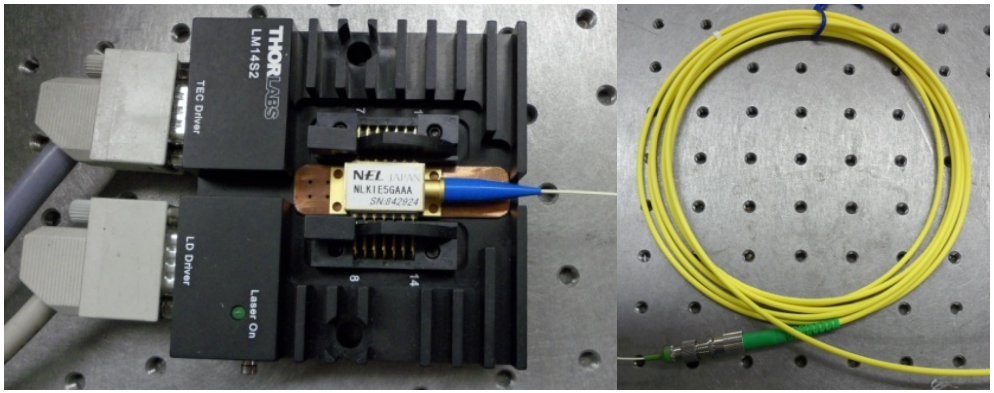
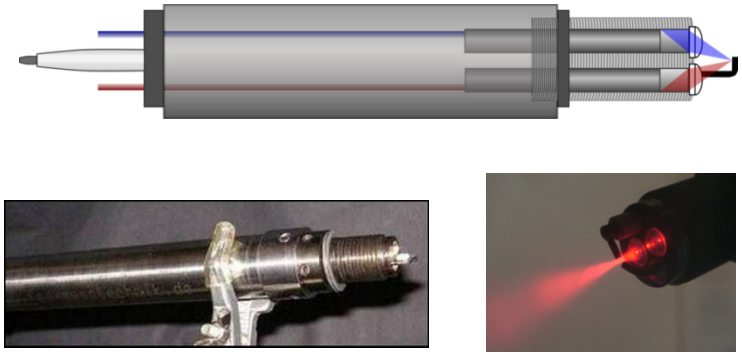
- Reliable components and easy operation without special training
- Applicable to real-world combustion systems

→ Fiber-based optical sensors in combination with (direct) absorption spectroscopy



DFB-diode laser, mounted

Glass fiber SMF-28



Fiber-coupled spark plug sensor

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Chapter 2: Benchmark Experiments

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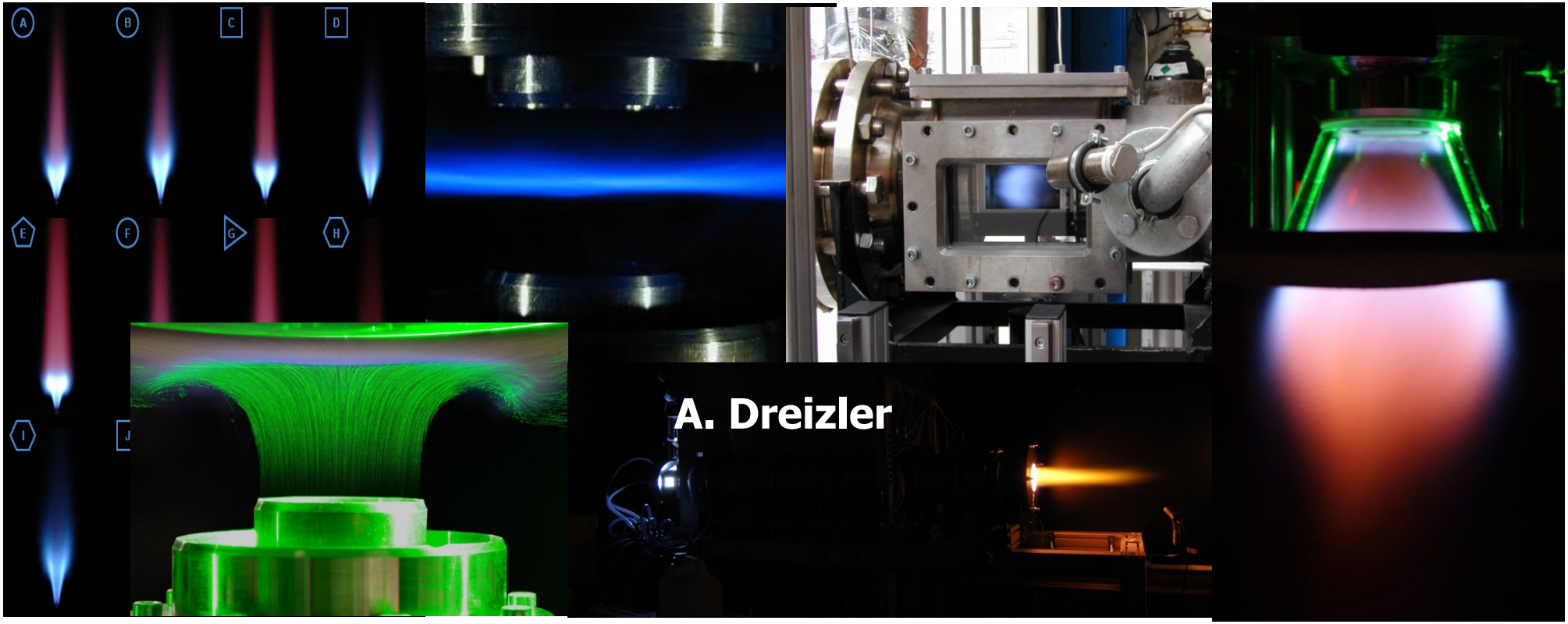


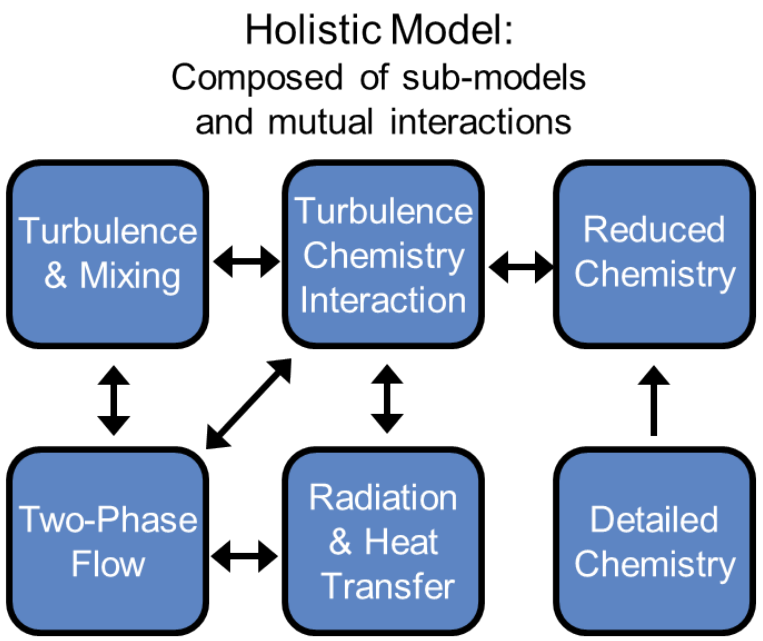
Validation of numerical simulations

- Experimental research in turbulent flames needs suitable generic combustion systems
- Numerical simulations are based on models
  - Turbulence model
  - Combustion model
  - Turbulence-chemistry interaction model
  - Spray model …

→Comp ts for **validation** and impro quisite

→(Qua ustion

→ Need for **ents** mimicking specific n systems



Bench mark flames/ configurations

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- **Requirements for optical diagnostics**
  - Optical access from three sides to enable application of different laser diagnostics
  - Nozzle exit accessible, such that radial profiles can be recorded as close as possible (~1mm)
  - Optical access to interior of nozzle (if possible)
  - In case of atmospheric flames shielding from the lab (co-flowing air)
  - Decoupling of the flame from the exhaust gas system
  - Fuel composition that does not interfere with the laser/ detection wavelength

Bench mark flames/ configurations

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- **Requirements for validation of numerical simulations**
  - Known or measurable inflow conditions
  - Well-defined boundary conditions
  - Parametric variation (“flame sequence”) of key-quantities such as
    - Fuel composition, equivalence ratio
    - Reynolds-number, thermal load
    - Swirl intensity
    - Pressure
    - Geometry

    → **Identify sensitivities**

From simple to complex – benchmark configurations at TUD

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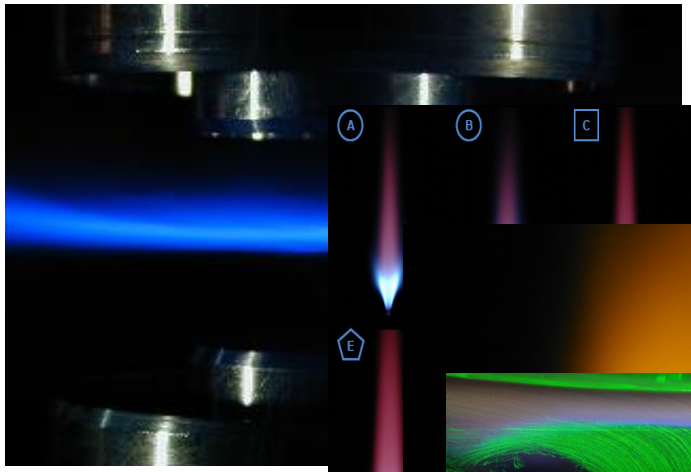
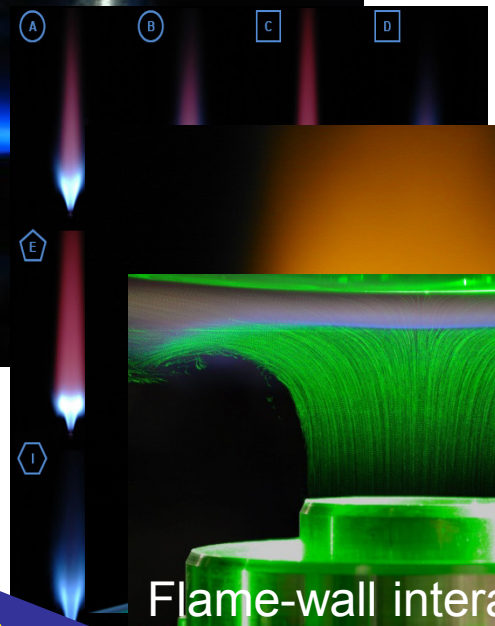
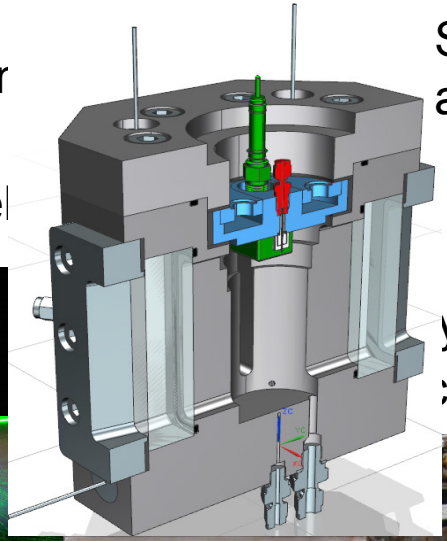




Flame-wall interaction

Turbuler

Fuel



Supercritical droplets and droplet combustion

propagation

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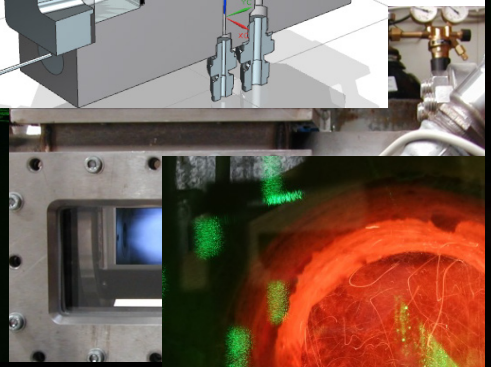

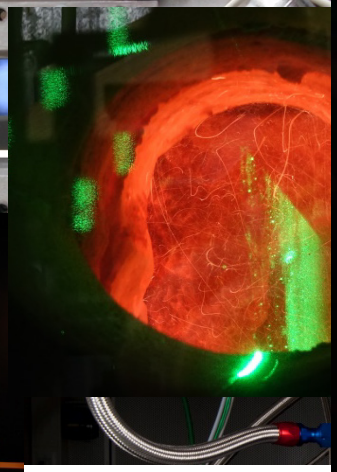

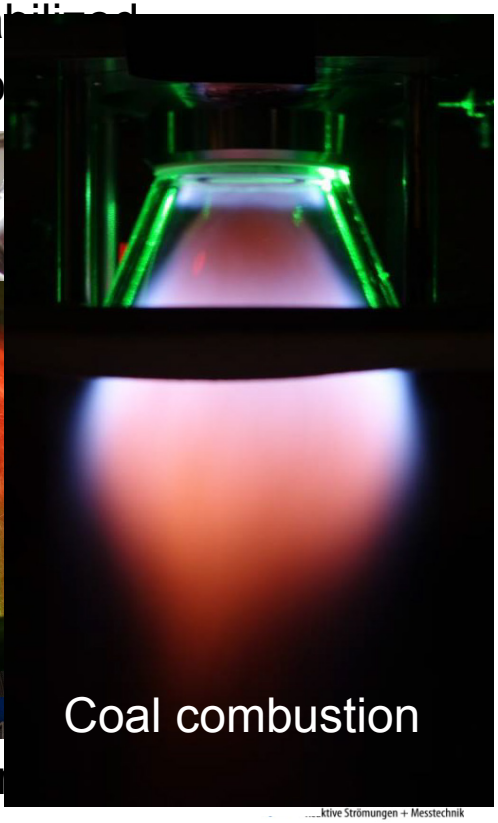

Coal combustion

Complexity

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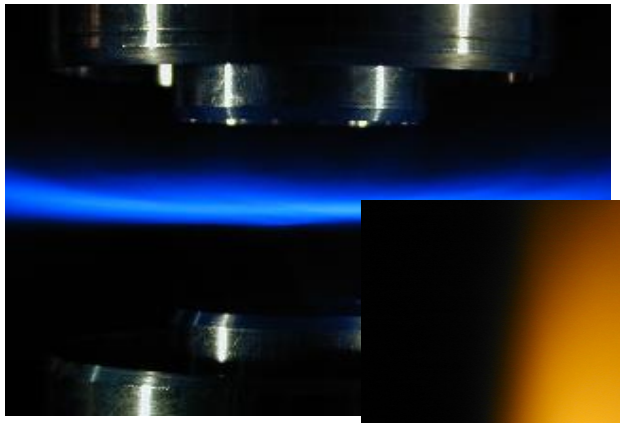
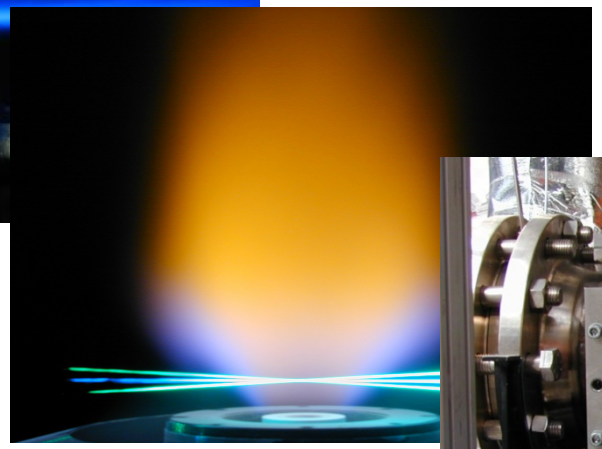
Bench mark configurations

- **3 Examples of bench mark flames**
- **1 Example of optically accessible IC-engine**

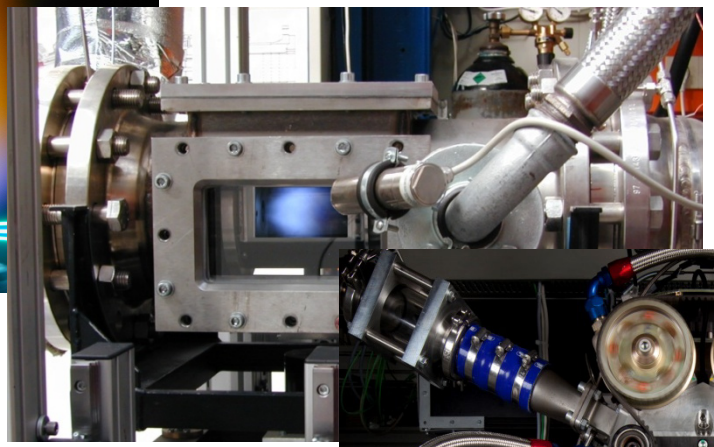


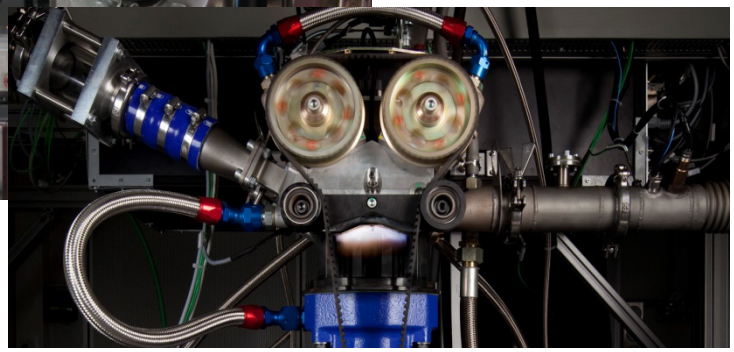
Turbulent opposed jets



Swirl/ bluff body stabilized

Enclosed combustor/ GT conditions

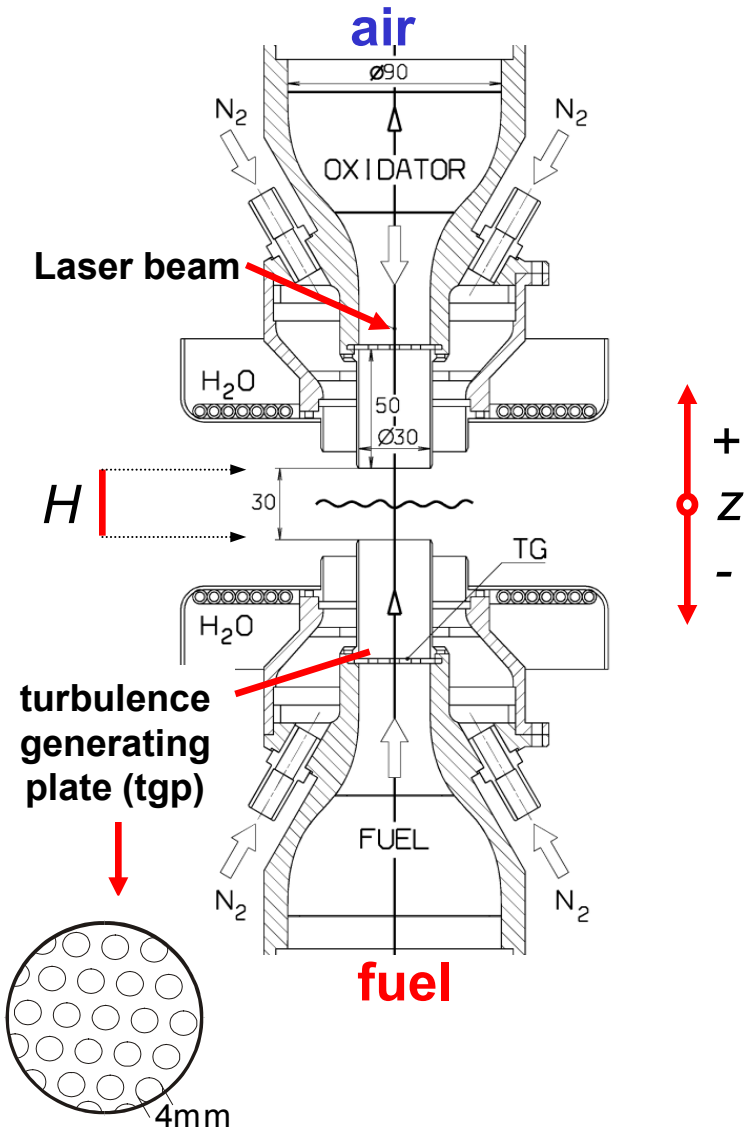




Transparent IC engine

Example 1: Turbulent opposed jet flame

- Two identical opposed nozzles, D=H=30mm
- Turbulence intensity ~0.07 at nozzle exit, enhanced by turb. grid (tgp)
- N_2 coflow prevents ambient air mixing
- Access laser beam along burner axis → no beam steering
- Horizontal stagnation plane → symmetric influence of gravity
- Water cooling for stable long term operation
- **Parametric variation**
  - Fuel composition
  - Reynolds-No. (stable to extinction)



Turbulent opposed jet flame

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- “Flame sequence” → Variation of fuel composition and Re
- Fuel: partially premixed methane/air (avoiding soot)

Re_{air}	a_m(1/s)	Φ = 3.18	Φ = 2.0	Φ = 1.6	Φ = 1.2
3300	115	TOJ1A			
4500	158	TOJ1B	TOJ2B	TOJ3B	TOJ4B
5000	175	TOJ1C	TOJ2C		
6650	235	TOJ1D	TOJ2D		
7200	255		TOJ2E		

Extinction limit

Turbulent opposed jet flame

- Flow field quantities for TOJ2D

Bulk velocity W_b	3.4m/s
Turbulent Re-number Re_t	90
Bulk strain rate $a_b = (-W_{b,O} + W_{b,F})/H$	231s $^{-1}$
Residence time in mixing layers $t_{res} = a_b^{-1}$	4.3ms
Large-eddy turnover time $t_{ov} = l_0/(2k)^{1/2}$	16.2ms
Integral time scale T at nozzle exit	1.6ms
Integral length scale l_0 at nozzle exit	4.7mm
Kolmogorov length scale η_K at nozzle exit	0.16mm
Batchelor scale at nozzle exit η_c	0.18mm

Turbulent opposed jet flame

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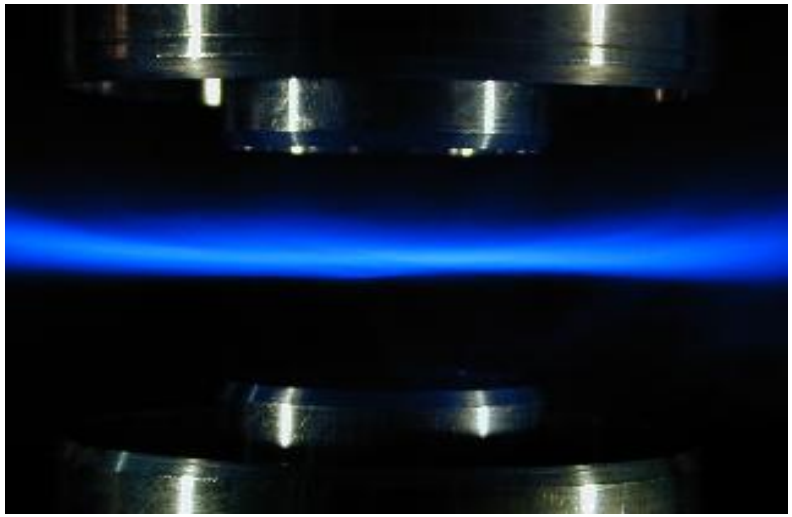
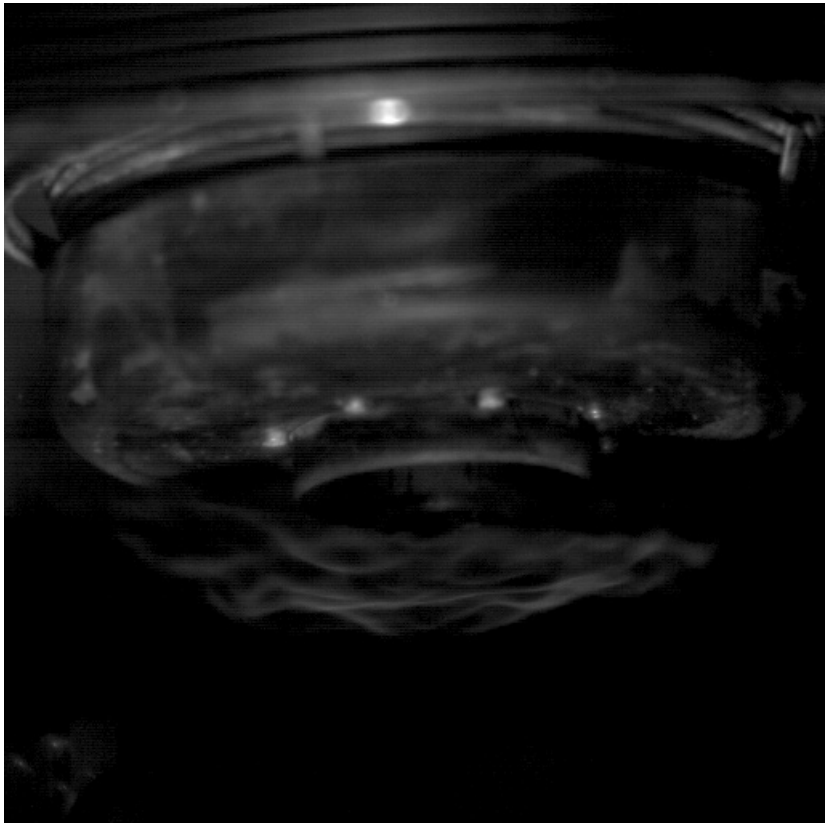
- **Visual impression**

Time-averaged flame luminosity



Transient flame luminosity

@ 500 Hz



Turbulent opposed jet flame

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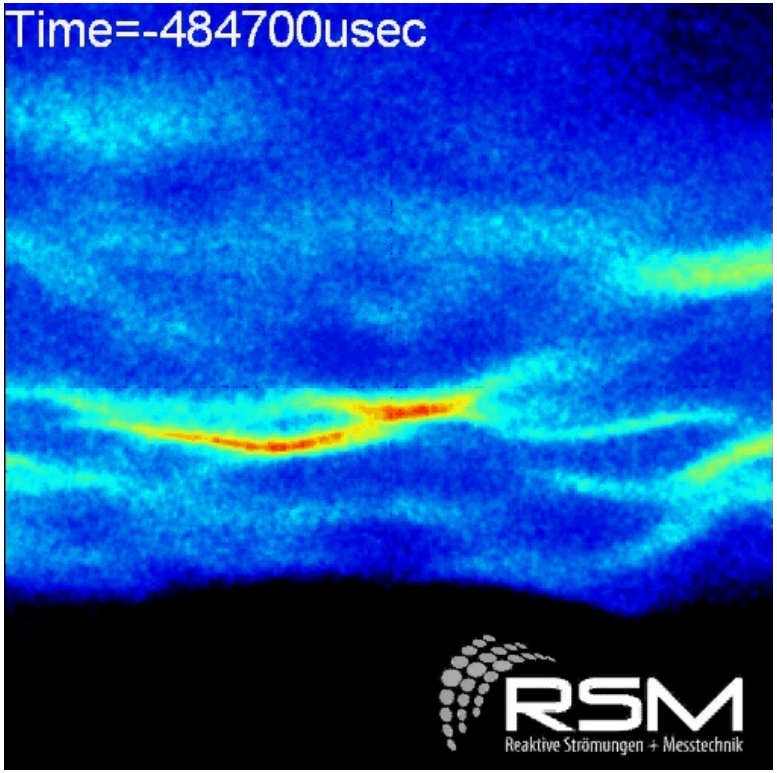
- Special feature of turbulent opposed jet flames:
  - Investigation of flame extinction by increasing strain close to critical value
  - Extinction monitored by temporally resolved chemiluminescence, **10 kHz**



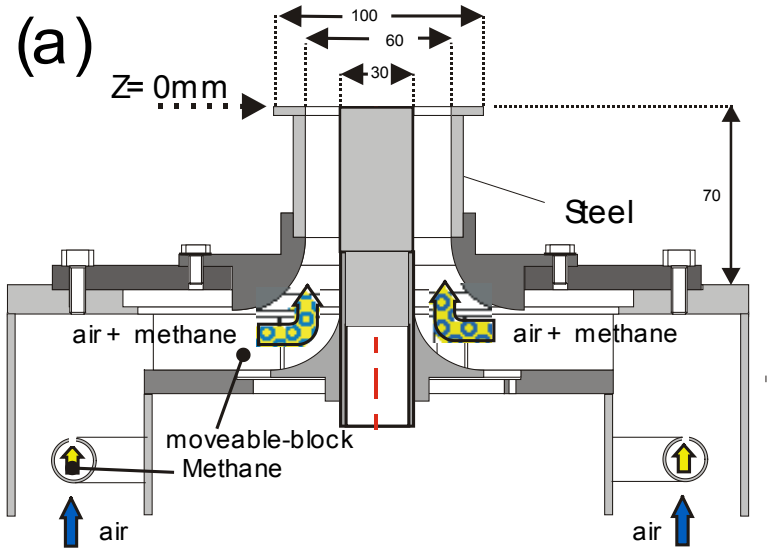
Bench mark configurations

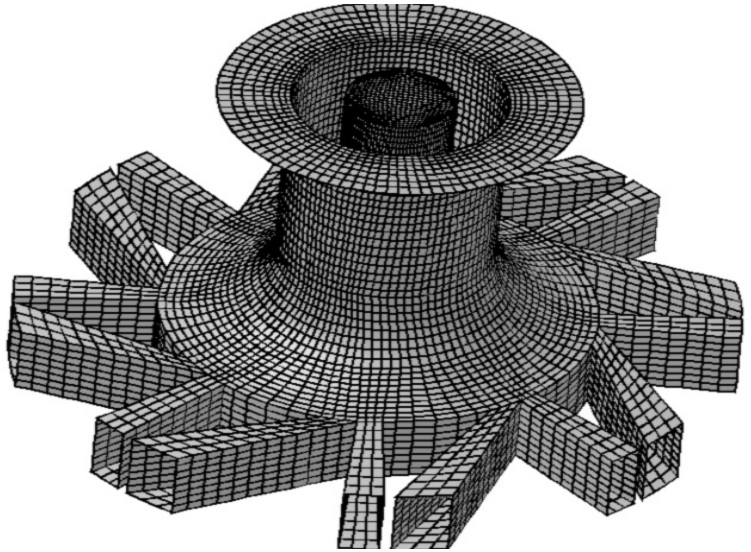
- **Example 2: Swirling lean premixed flame**
  - Relevant for flame stabilization in real combustors
  - Complex chemistry and complex flow field properties

Swirling lean premixed flame

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Nozzle closer to practical applications**
- **Need for reliable data sets of premixed flames**
- **Parametric variation of**
  - Reynolds number
  - Swirl number
  - Equivalence ratio





Swirling lean premixed flame

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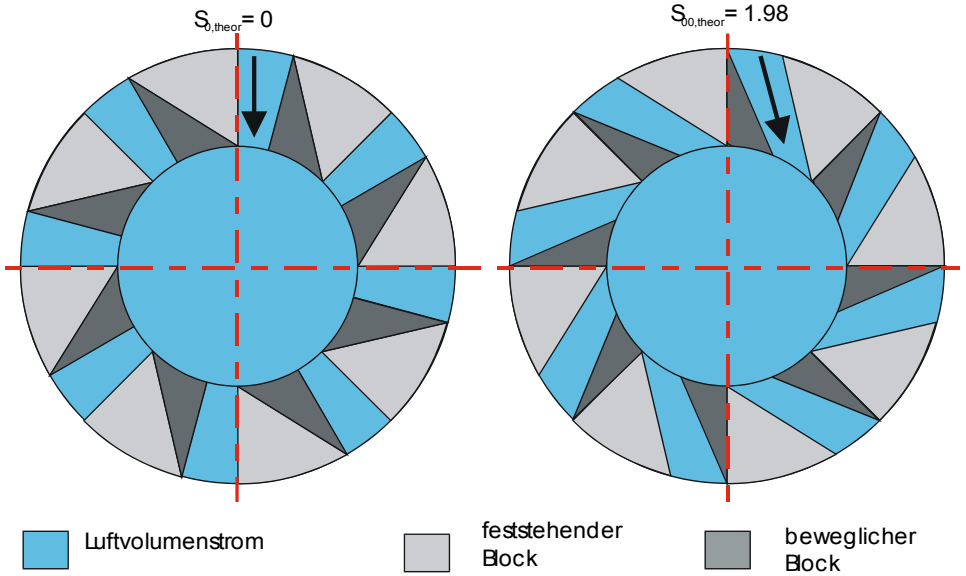
- **Swirl number**

$$S = \frac{G_\theta}{\frac{d}{2} \cdot G_x}$$

G_θ Axial flux of tangential momentum
G_x Axial flux of axial momentum

- **Variation by moveable block (motor driven, gear reduction)**



Swirling lean premixed flame

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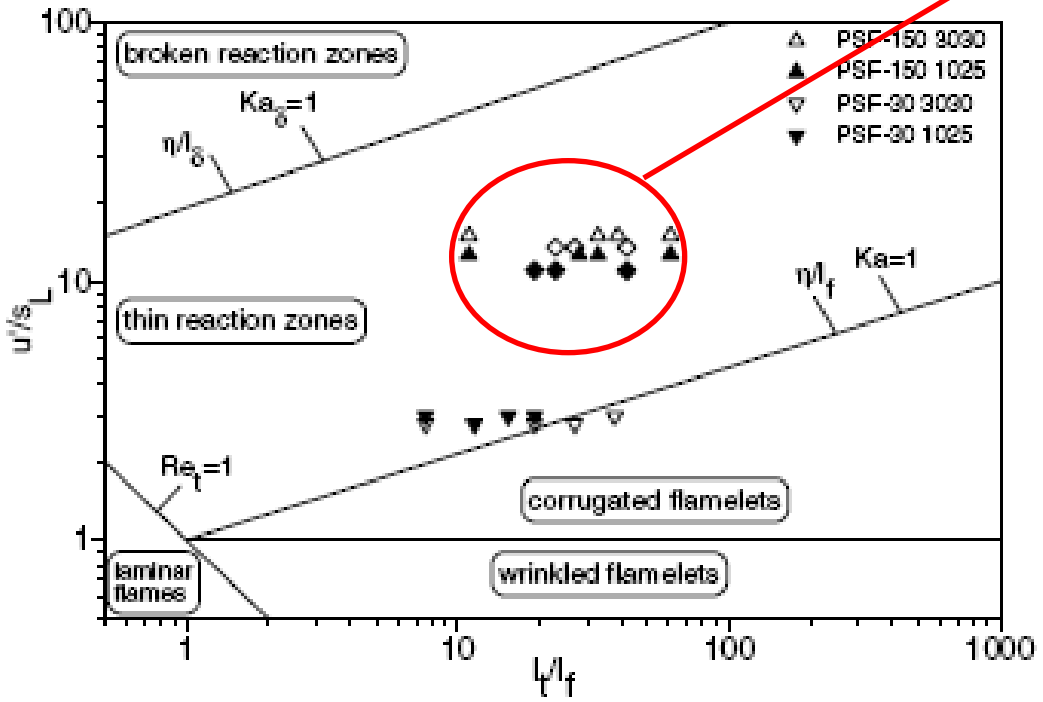
- **Parametric variation: Re**

		PSF-30	*PSF-90*	*PSF-150*
$S_{0,th}$	[-]	0.75	0.75	0.75
P	[kW]	30	90	150
ϕ	[-]	0.833	0.833	1.0
Q_{gas}	[m_n^3/h]	3.02	9.06	15.1
Q_{air}	[m_n^3/h]	34.91	104.33	145.45
$Re_{tot.}$	[-]	10000	29900	42300
s_L	[m/s]	0.36	0.36	0.42
l_F	[m]	$0.26 \cdot 10^{-3}$	$0.26 \cdot 10^{-3}$	$0.18 \cdot 10^{-3}$

Swirling lean premixed flame

- **Classification in regime diagram**

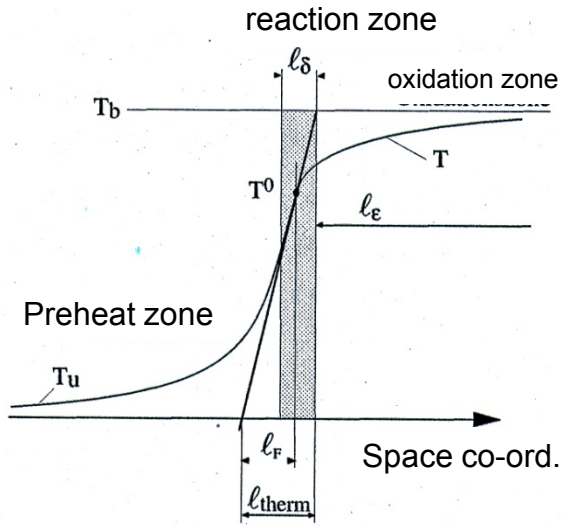
Small eddies penetrate only in preheat zone → flamelet-like-structure preserved



Velocity fluctuation/ laminar flame speed

Turbulent length scale/ laminar flame thickness

Laminar flame: T-profile



Swirling lean premixed flame

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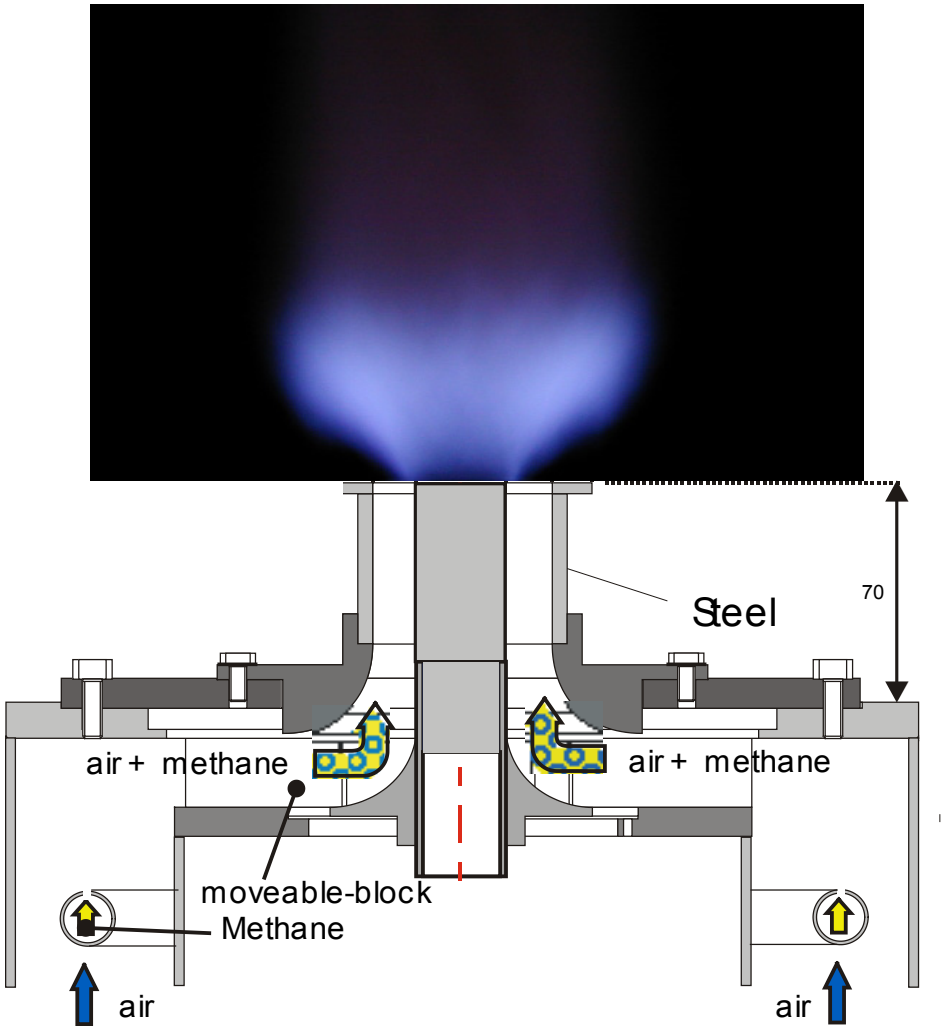
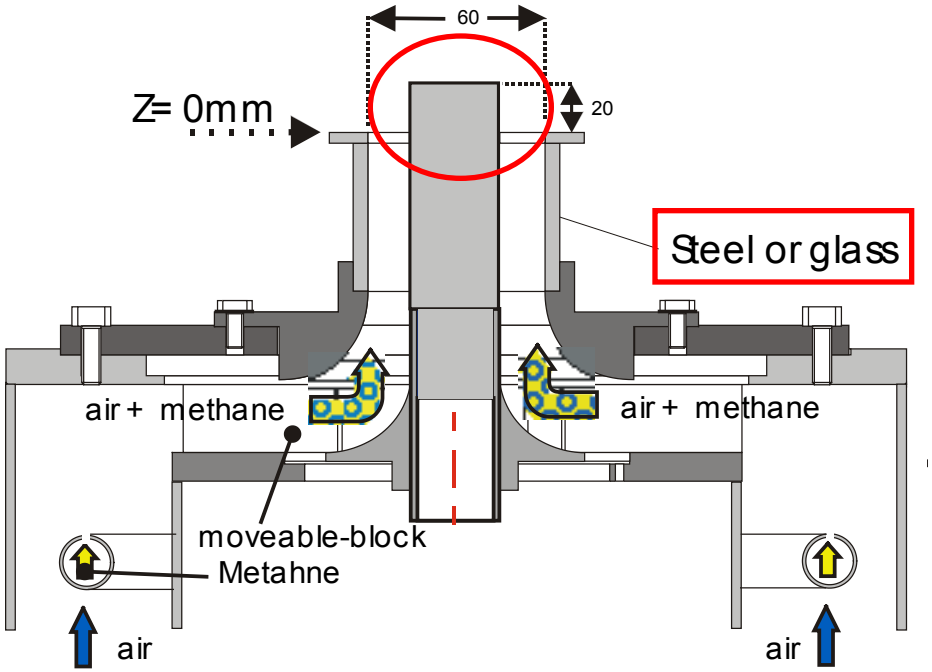
- **Visual impression**



Swirling lean premixed flame

- **Transition into flashback**
  - Variation of swirl number
  - Variation of equivalence ratio
- **Slight adaptation of nozzle geometry**
  - Extension of bluff body



Swirling lean premixed flame

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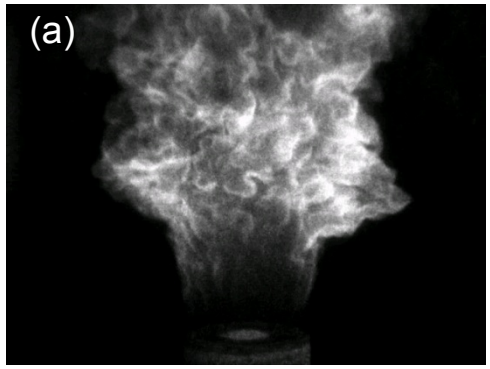
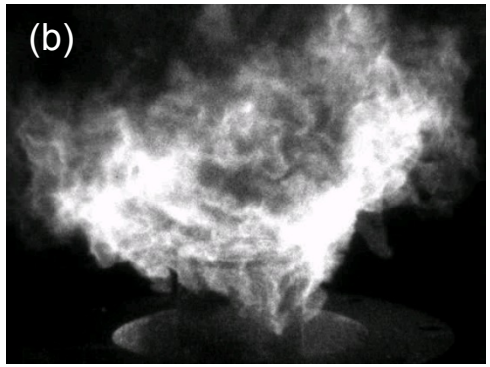
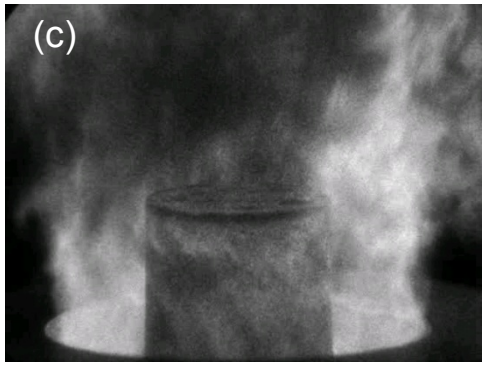
- **Three states of operation**



Stable: stabilization at the edge of the bluff body



Spinning: flame precesses around the shell of the bluff body



After flashback: the flame is stabilized at the swirler

Swirling lean premixed flame

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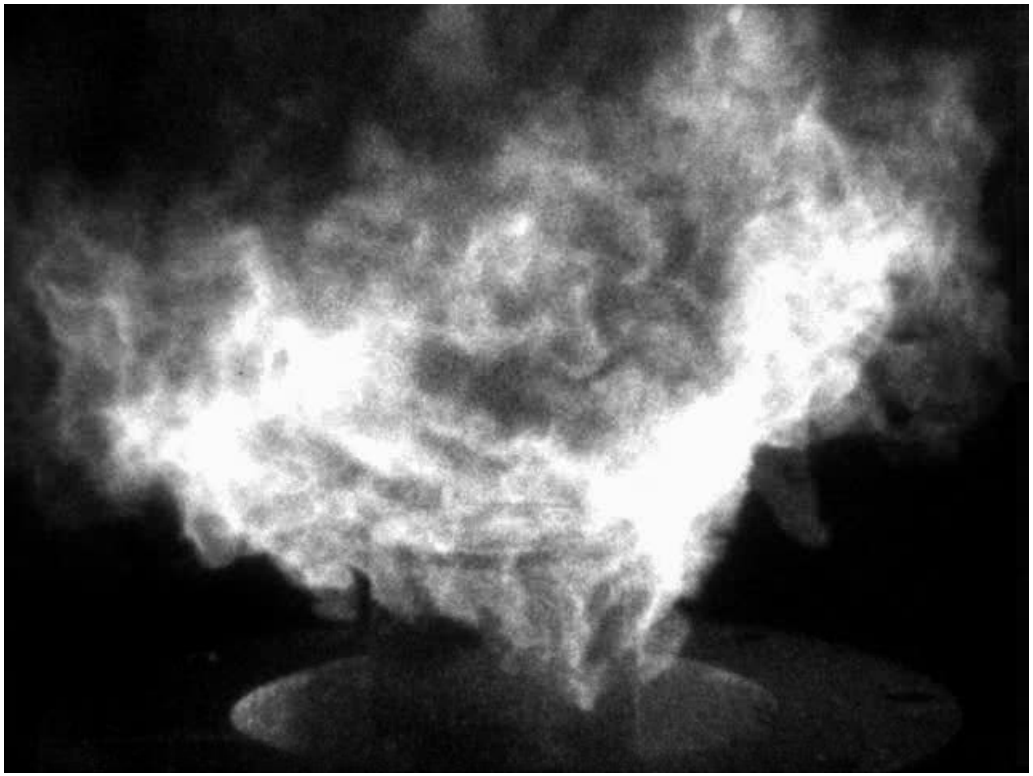
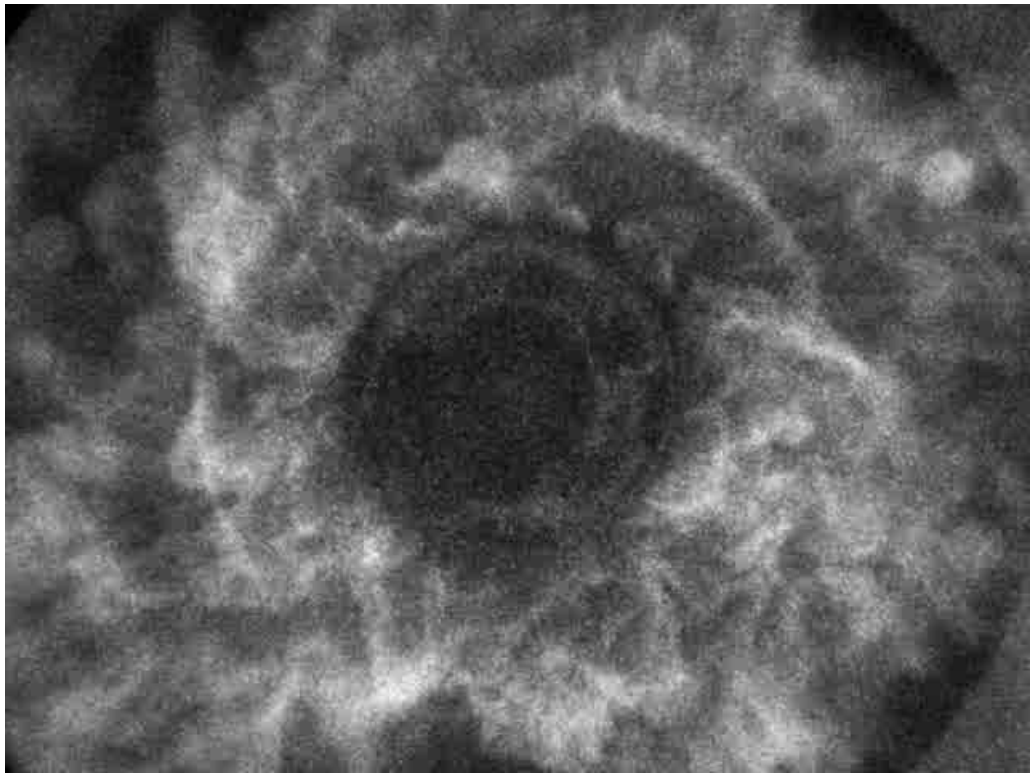
- **Precessing flame**

Meta-stable





Swirling lean premixed flame

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- **Precessing flame**

Flashback

Swirling lean premixed flame

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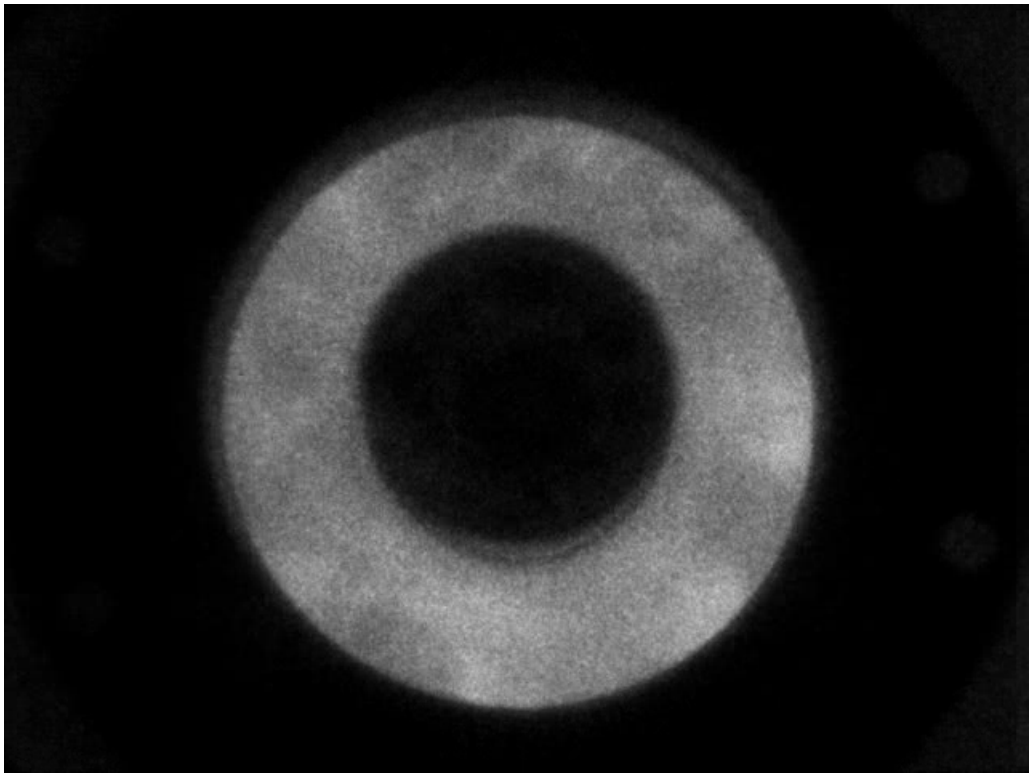
- **After flash back: view from top (slightly tilted)**



Swirling lean premixed flame

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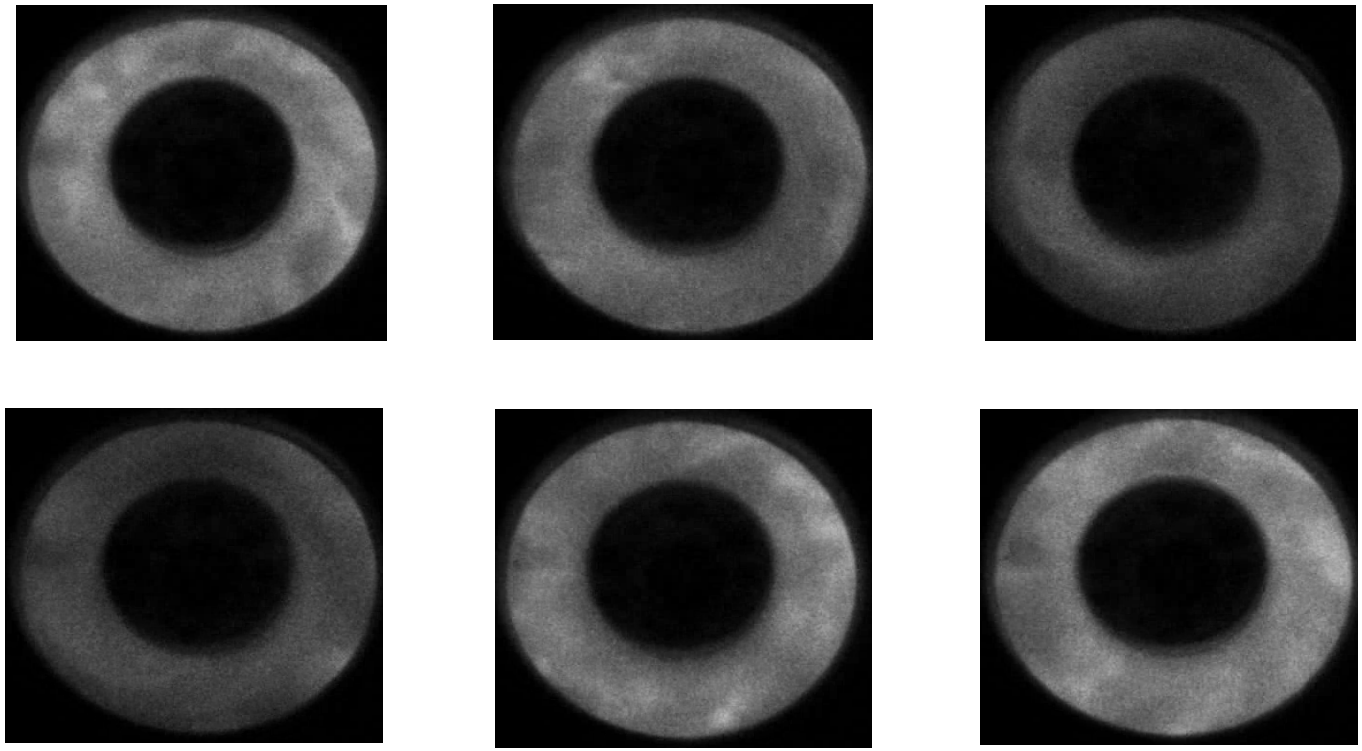
- **After flash back: view from top (slightly tilted)**

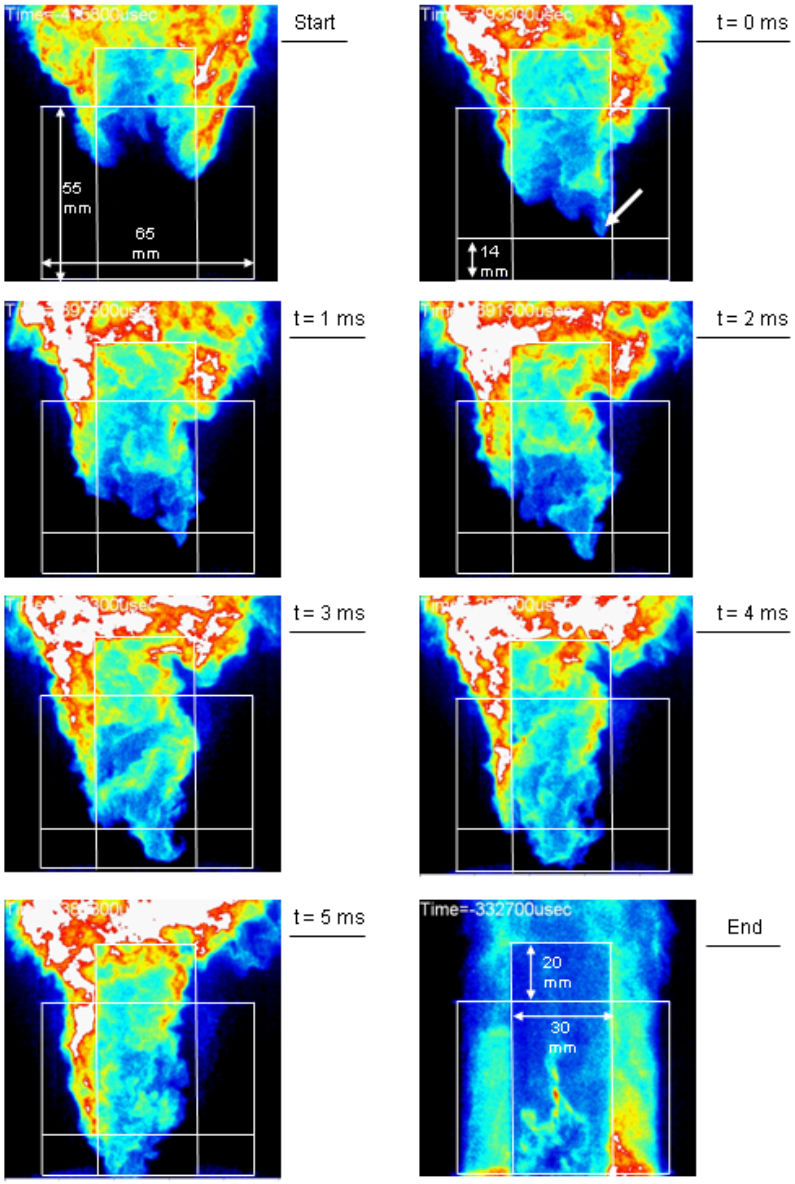


  - Flame luminescence monitored by intensified CMOS-camera at a frame rate of 7kHz
  - Only 6 exposures of a full cycle are shown
  - Cycle duration ~7.5±0.6ms.

Swirling lean premixed flame

TECHNISCHE UNIVERSITÄT DARMSTADT

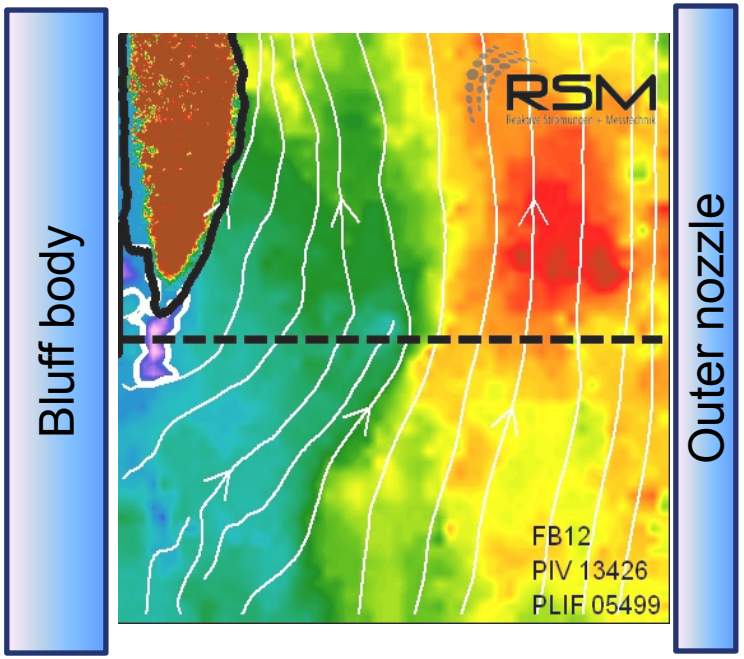
- **Transition from spinning into flashback**
  - Transparent nozzle
  - Chemiluminescence recorded at high repetition rates (kHz-regime)



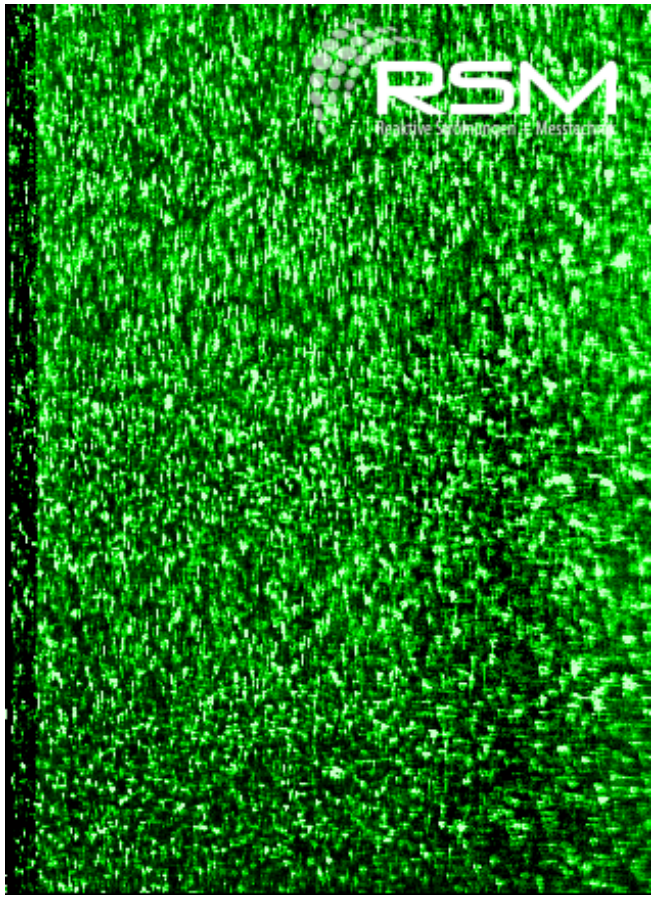
Swirling lean premixed flame

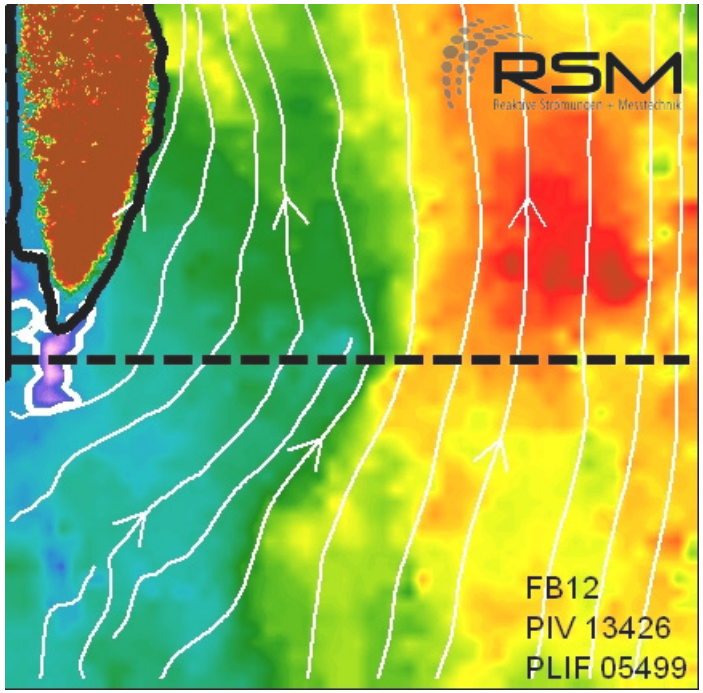
TECHNISCHE UNIVERSITÄT DARMSTADT

- **Transition from spinning into flashback**
  - Transparent nozzle
  - OH-PLIF and 2C-PIV recorded at high repetition rates (kHz-regime)



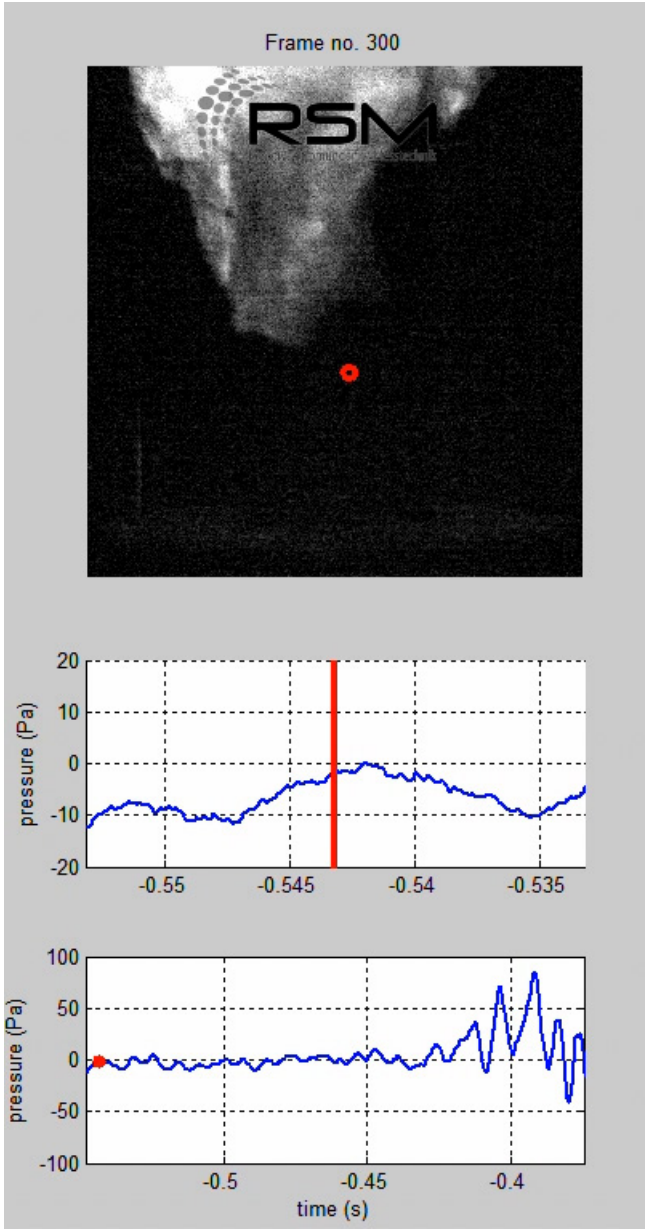
Swirling lean premixed flame





Swirling lean premixed flame

- **Transition from spinning into flashback**
  - Simultaneous optical and pressure measurements
  - Multi-parameter diagnostics crucial for better understanding



Swirling lean premixed flame

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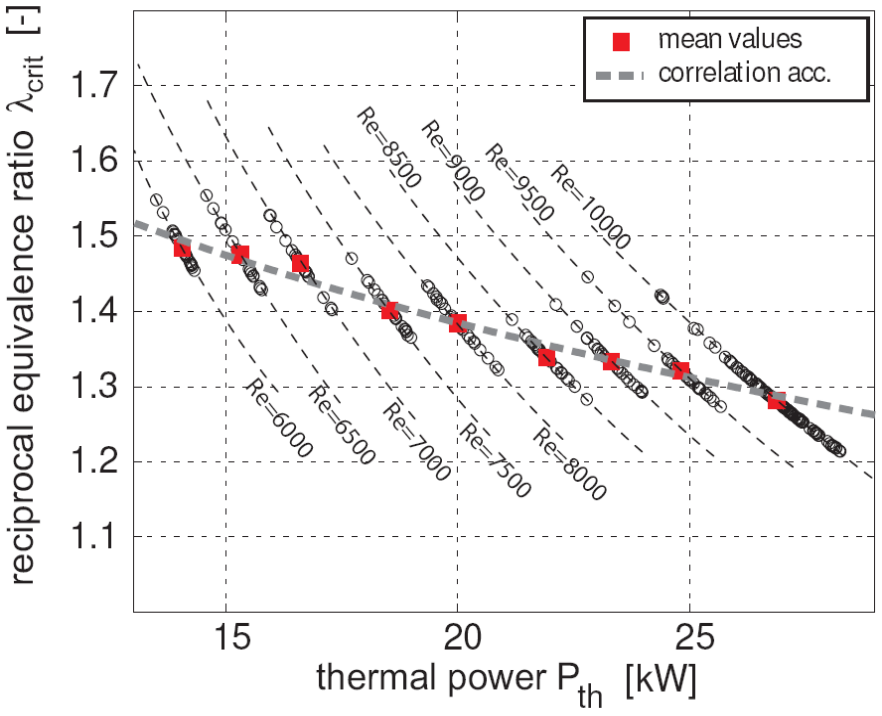
- **Stability map**
  - For fixed geometrical swirl number



  - Flashback is favored by
    - Lower Reynolds numbers
    - Higher laminar flame speeds
    - Higher swirl intensity (not shown in this graph)

Bench mark configurations

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- **Example 3: enclosed pressurized flames**
  - Non-premixed natural gas flames or spray flames and lean premixed flames
  - Mimicking performance of real combustors but only single nozzle (for example circumferential modes in annular combustors not accessible)

Enclosed pressurized flames

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- **Modular setup**
  - Pressure housing
  - Optically accessible flame tube
  - Complex infrastructure
    - Pressurized air supply
    - Electrical heating of combustion air to mimic inlet conditions of GT-combustor
    - Pressurized fuel supply
      (natural gas compressor, for liquid fuels high pressure pump and large storage capacity)
    - Exhaust gas treatment (cooling)
    - Safety equipment (sensors and explosion protection)

Enclosed pressurized flames

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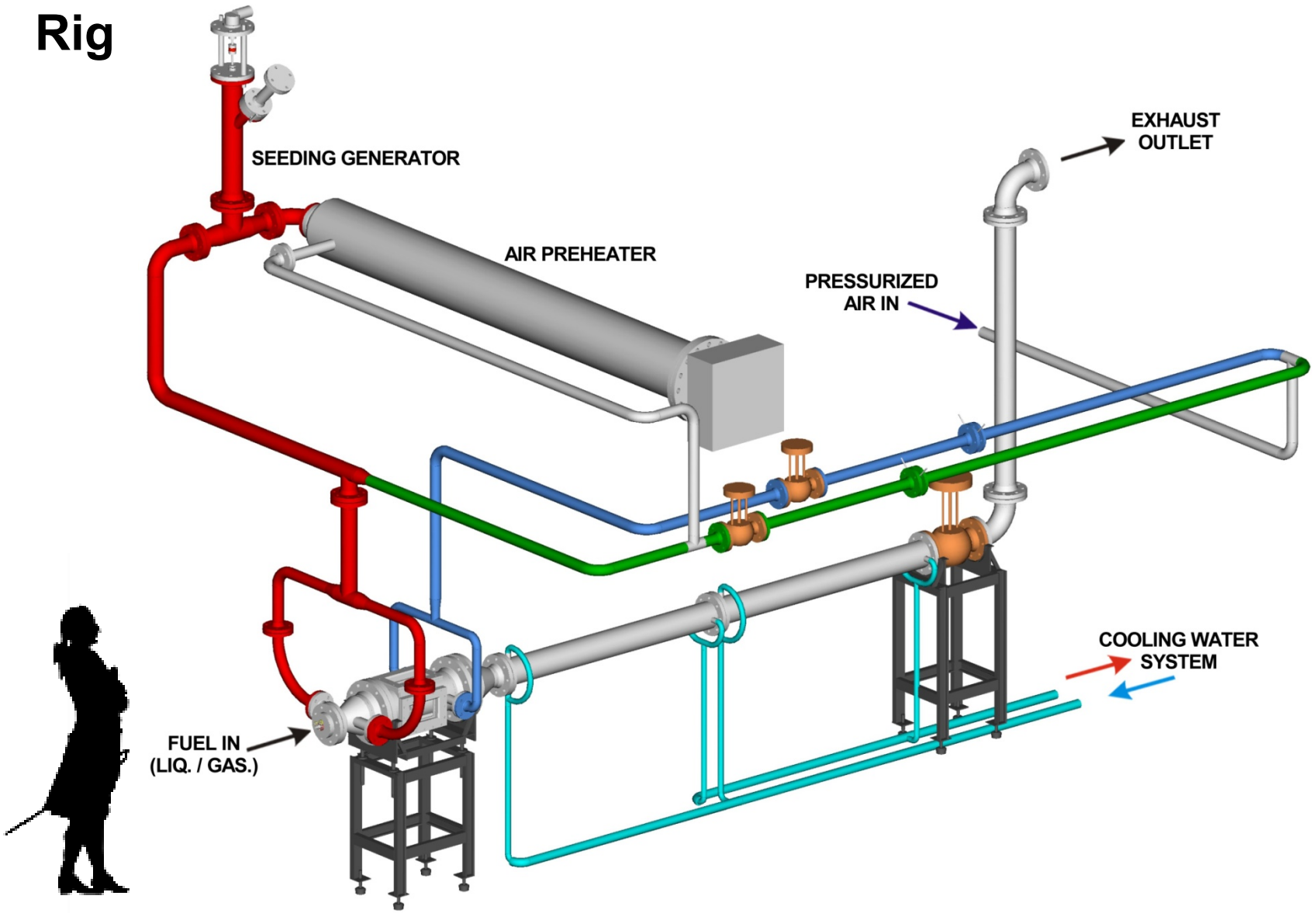
- **Rig**



Enclosed pressurized flames

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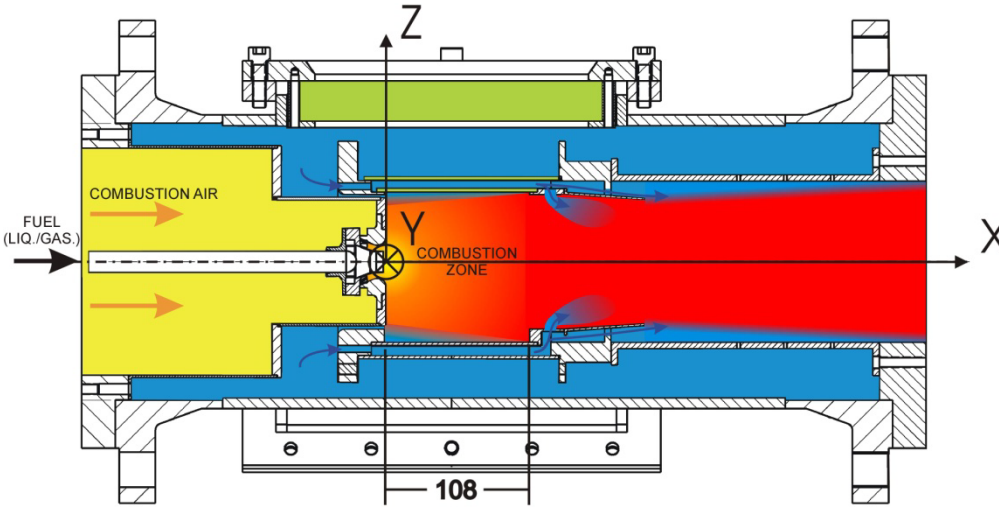
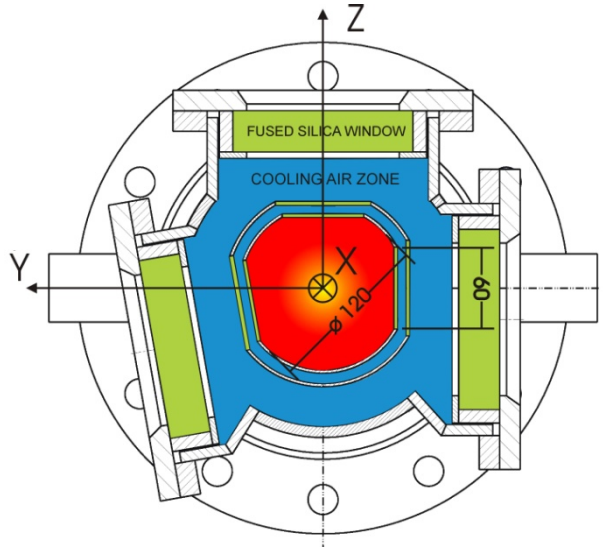
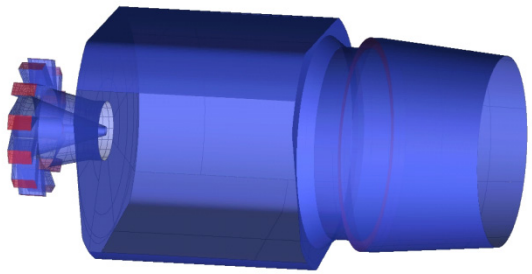
- **Optically accessible combustor**
- “Can-combustor-concept”
- P_{max}=10bar, T_{max}=773K
- Modular to adapt different geometries/ combustion concepts
- Optical access from three sides for LDA/PDA, PIV, LIF, CARS, etc.
- No disturbance of primary reaction zone by cooling air
- CAD-design for computational meshes







Enclosed pressurized flames

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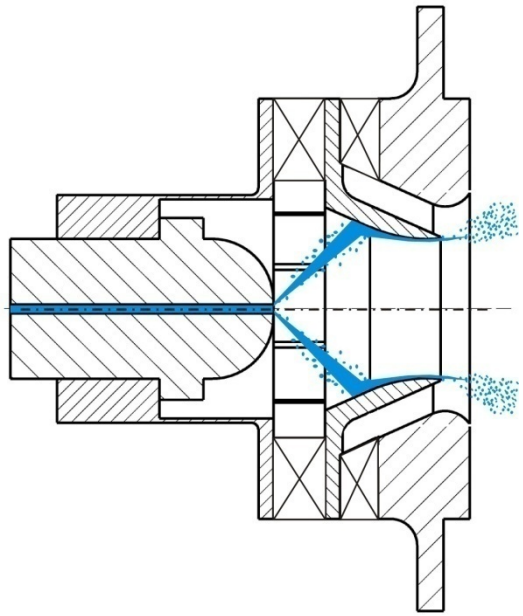
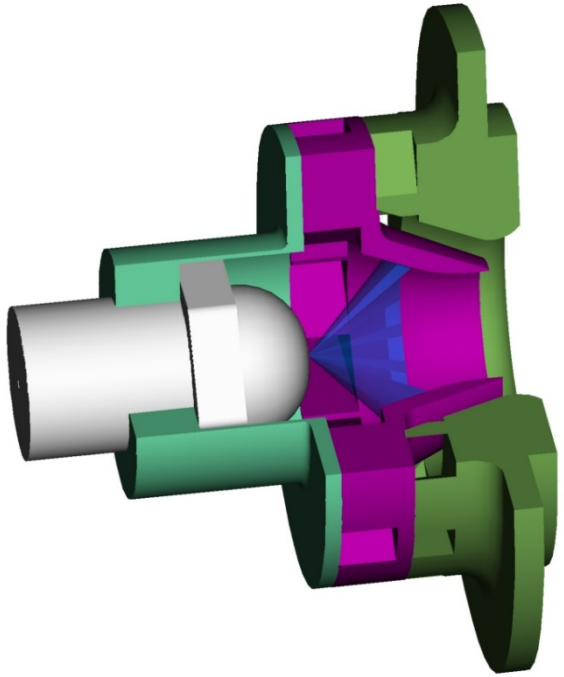
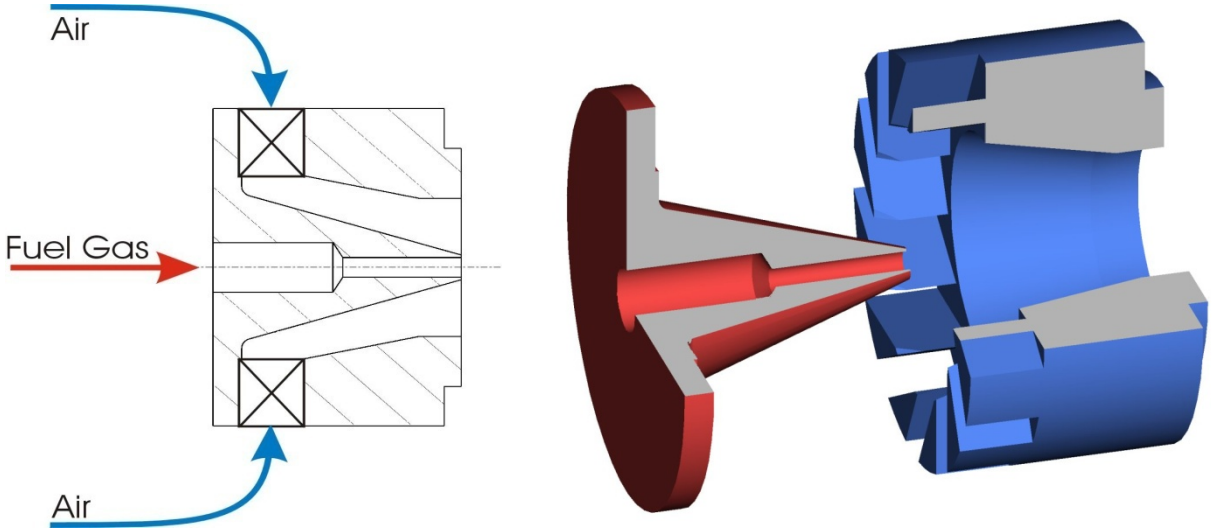
- **Nozzles**
  - Spray flames: n-heptane / air
  - Surrogate n-heptane advantageous compared to kerosene due to chemical kinetics modeling and spectroscopic properties





Enclosed pressurized flames

- **Nozzles**
  - Non-premixed gaseous flame: Natural gas / air



- Simple, generic design
- Non-reactive conditions: Mixture of helium and air to match density
- Swirl number from geometry S=1

Enclosed pressurized flames

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- **Operational conditions**

Pressure	2bar	4bar	6bar
Combustion air temperature	623K	623K	623K
Fuel temperature	373K	373K	373K
Combustion air mass flow	30g/s	60g/s	90g/s
Re_{Air}	46000	92000	138000
Re_{Fuel}	33000	67000	100000

Enclosed pressurized flames

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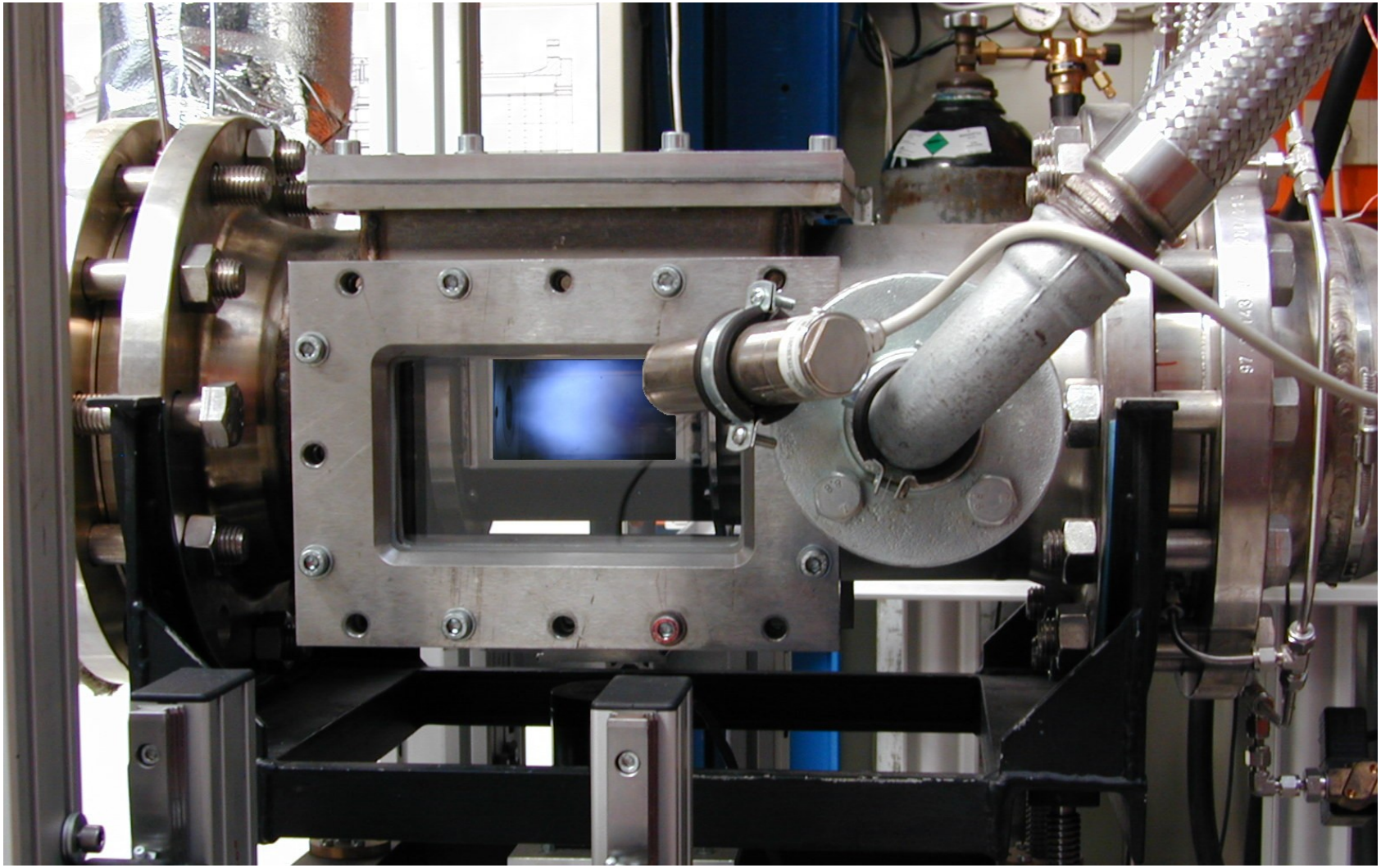
- **Visual impression**



Enclosed pressurized flames

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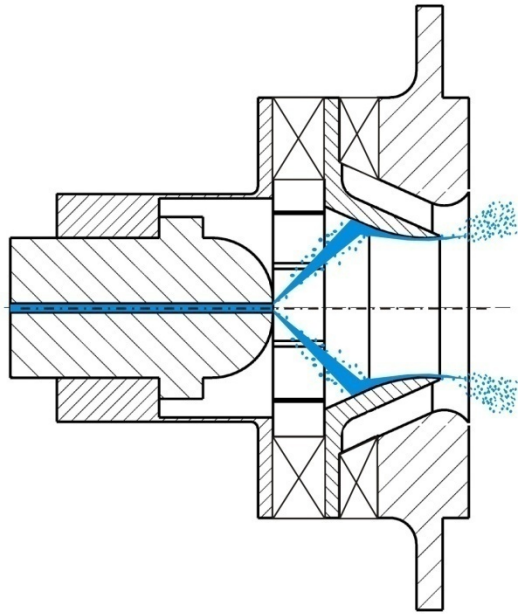
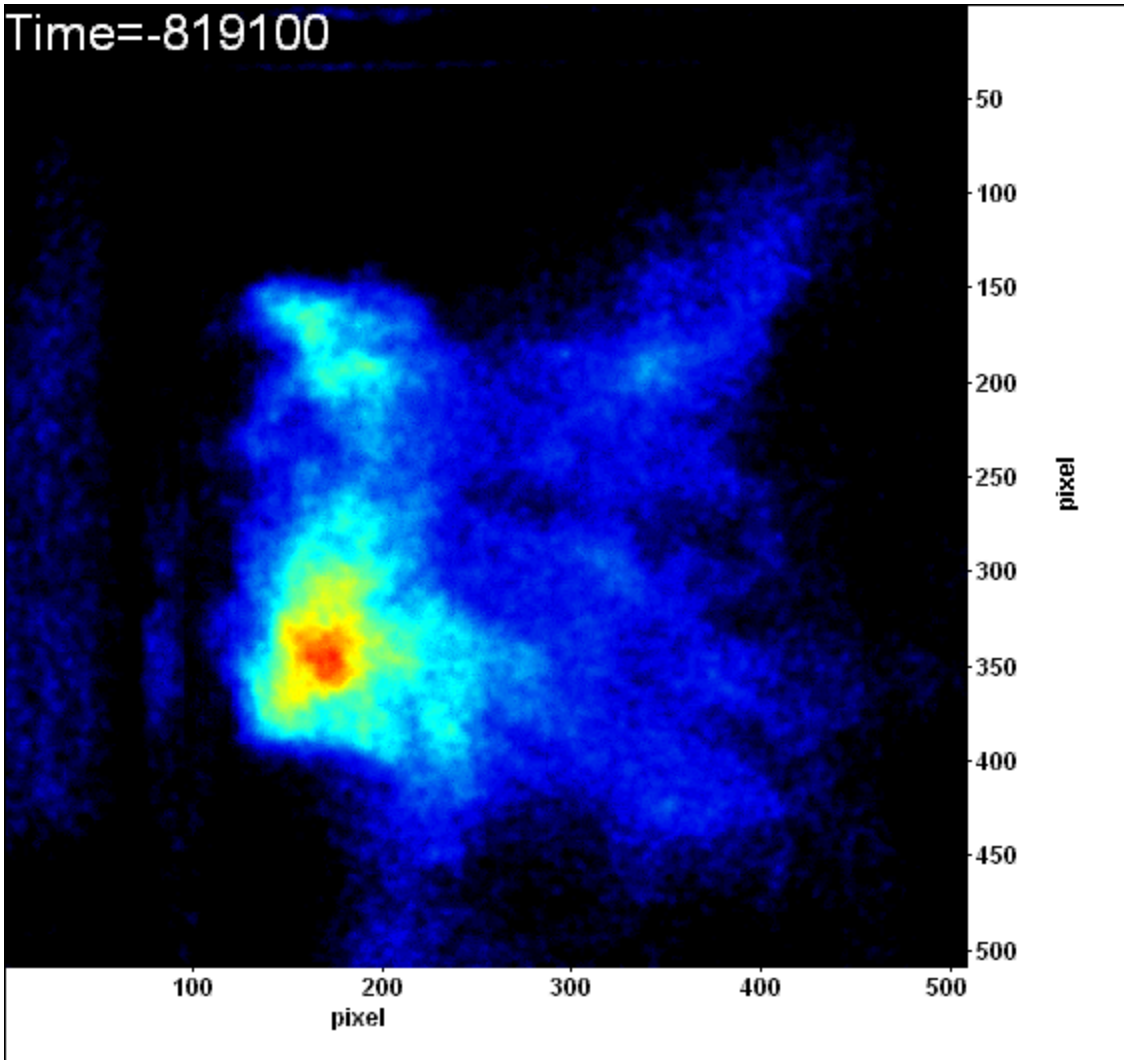
- **Visual impression – chemoluminescence of spray flame**





Enclosed pressurized flames

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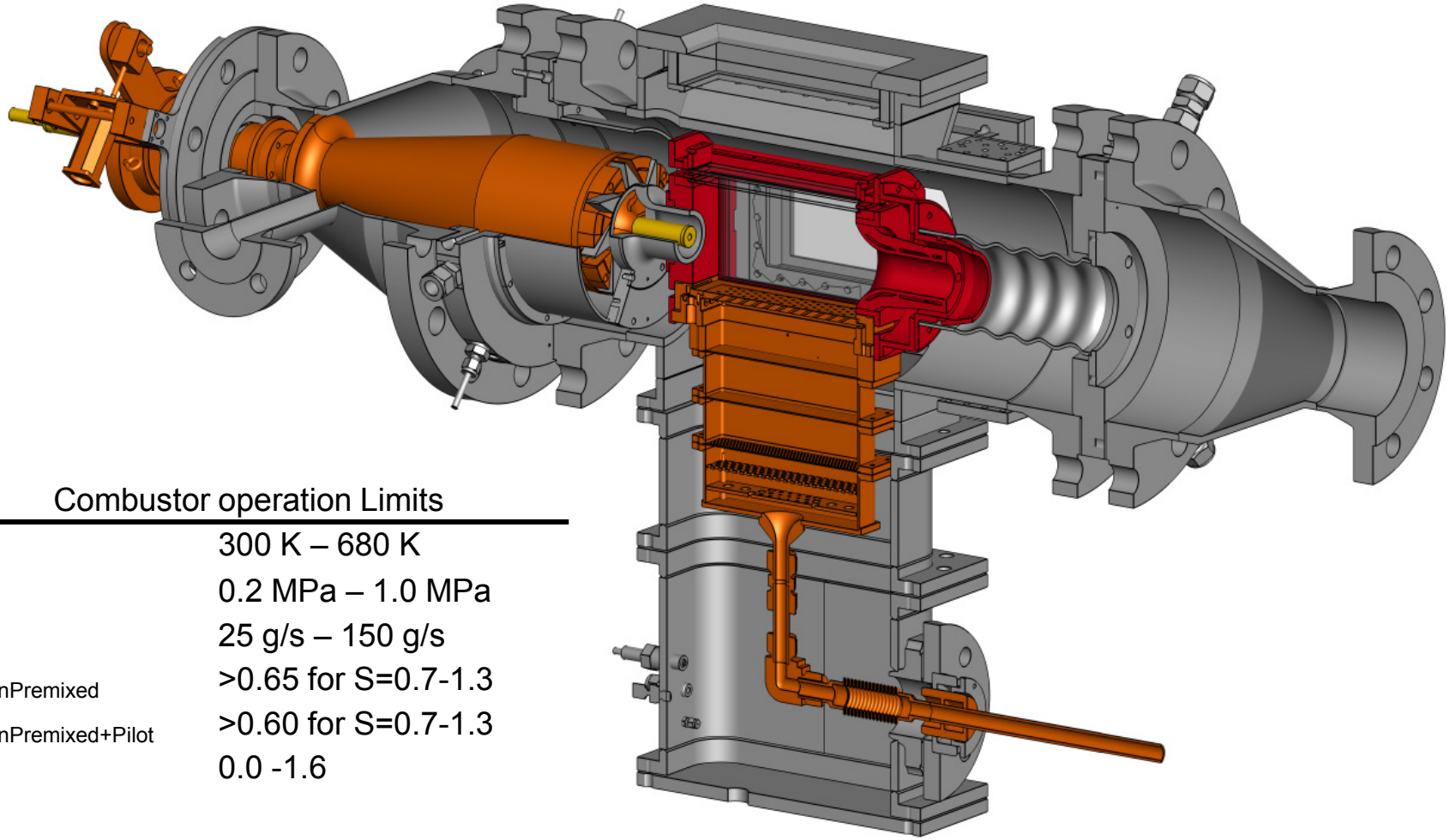
- **Present research: Effusion cooling**



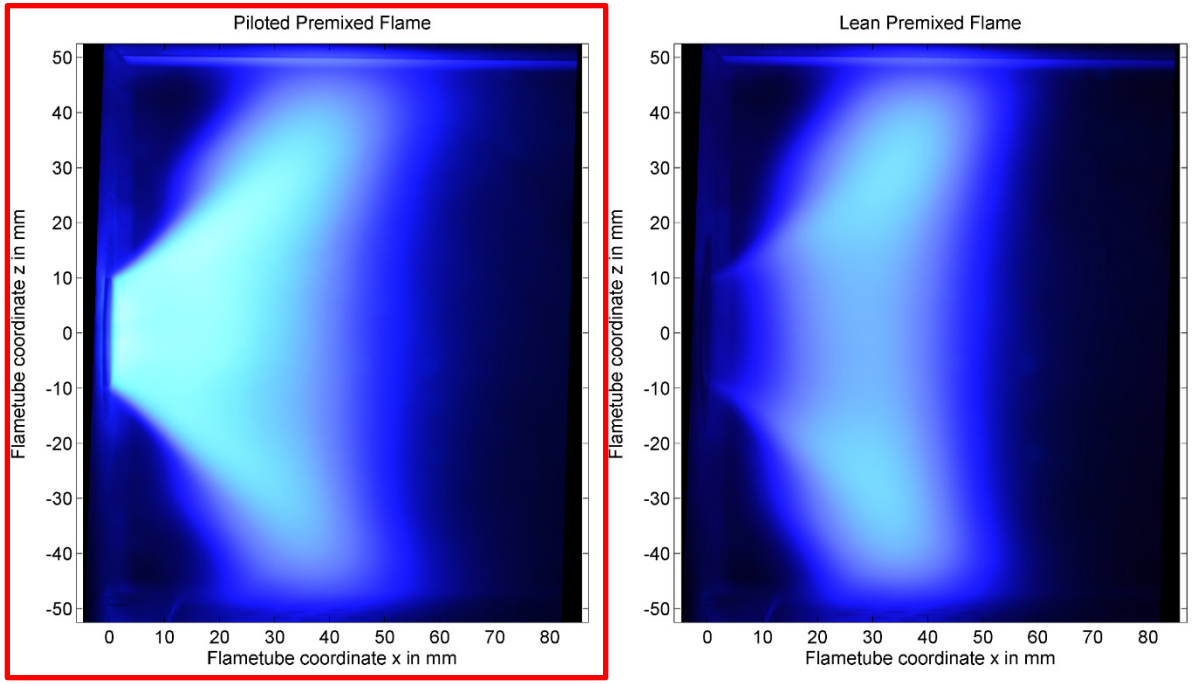
Combustor operation Limits	
T_3	300 K – 680 K
P_3	0.2 MPa – 1.0 MPa
m_3	25 g/s – 150 g/s
$\varphi_{LeanPremixed}$	>0.65 for S=0.7-1.3
$\varphi_{LeanPremixed+Pilot}$	>0.60 for S=0.7-1.3
S	0.0 -1.6

Enclosed pressurized flames

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Present research: Effusion cooling**

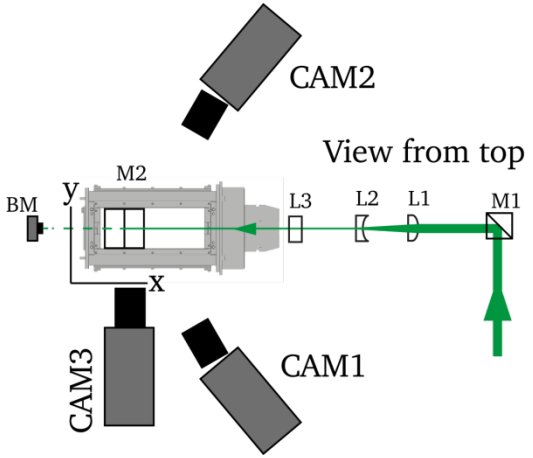
Operation conditions	
T_3	623K
P_3	0.25 MPa
$\dot{m}_3$	0.030kg/s
$\Phi_{LeanPremixed}$	0.65/0% Pilot
$\Phi_{LeanPremixed+Pilot}$	0.65/10% Pilot
S	0.7
$\dot{m}_5$	0.0125 kg/s
T_5	623 K

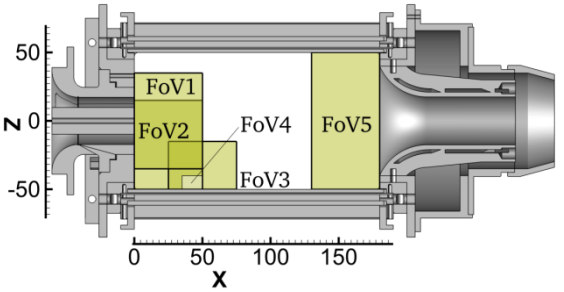


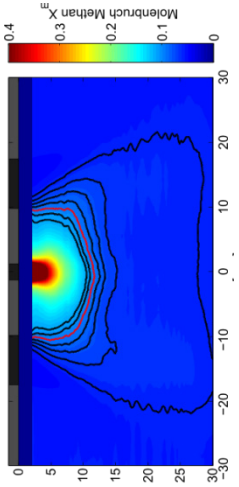
Low-pass (490nm) filtered Chemiluminescence images from piloted and premixed flames

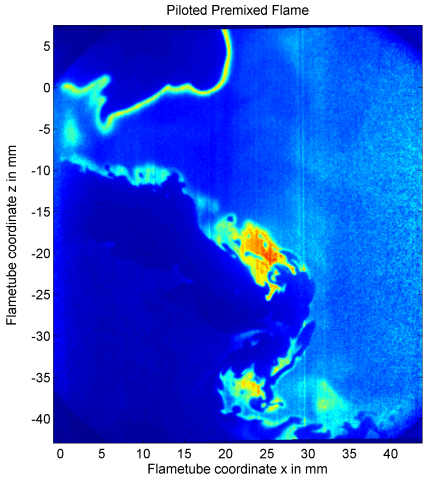
Enclosed pressurized flames

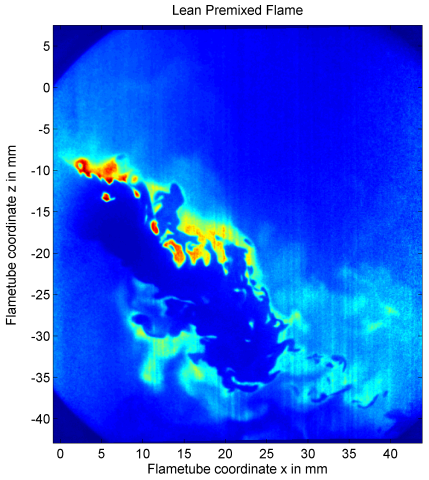
- **Present research: Effusion cooling**
  - Flow field: 2C and 3C PIV
  - Flame brush: OH-PLIF
  - Mixing fields: Acetone PLIF
  - Gas temp: CARS
  - Surface temp: phosphor thermometry











Enclosed pressurized flames

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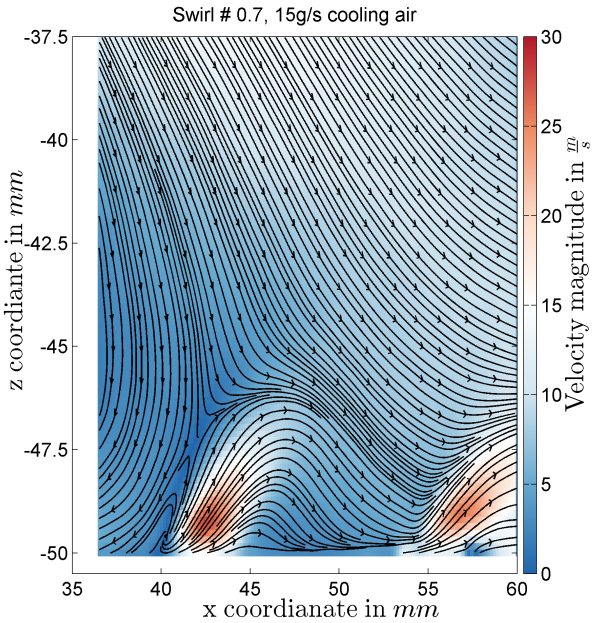
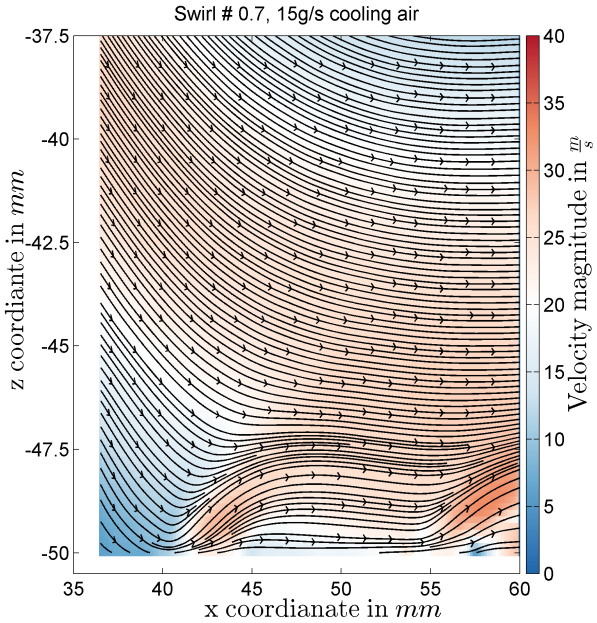
- **Present research: Effusion cooling**
- **Particle Image Velocimetry - PIV**

without pilot



with pilot



Enclosed pressurized flames

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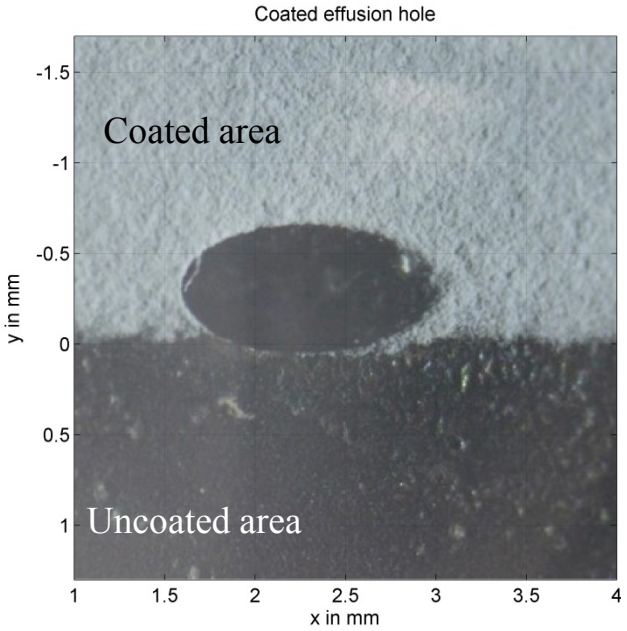
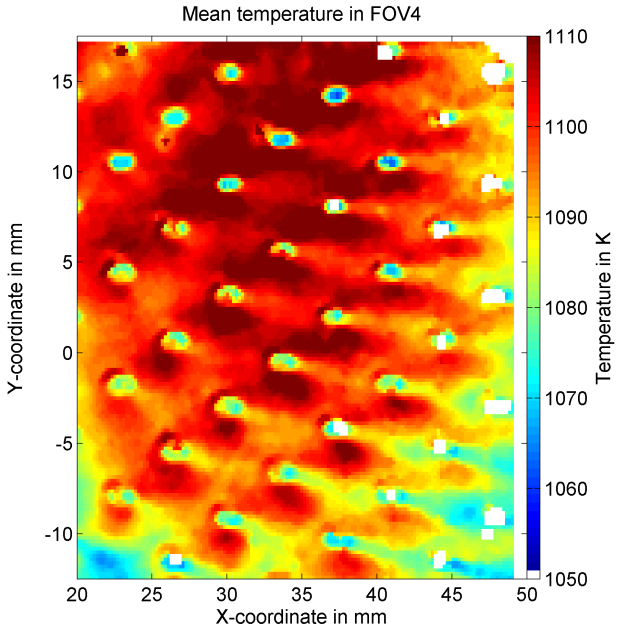
- **2D wall temperature**

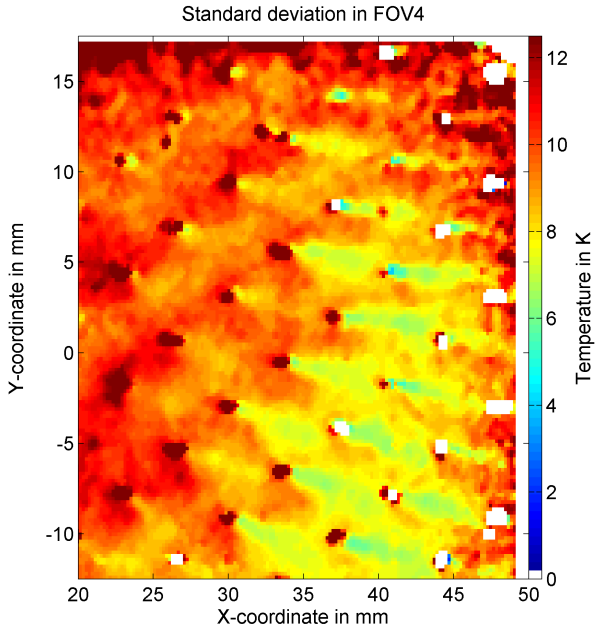
Magnified view of the coated liner.

Coating thickness t 10um <t <50um



Mean and standard deviation from 500 single shots at the liner surface

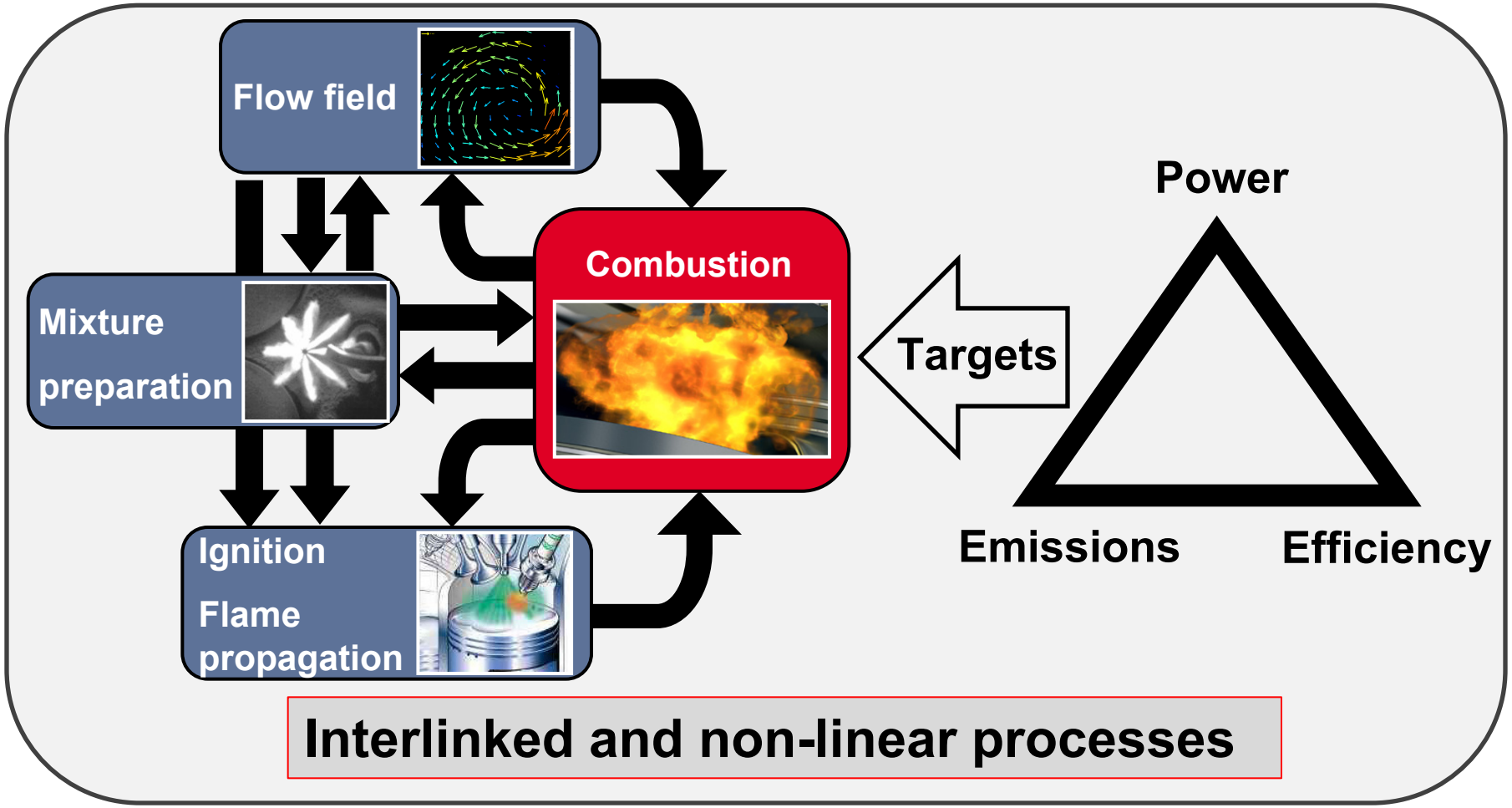




- Temperature measurement in flame wall contact zone at 20mm < x < 45mm
- Influence of cooling film visible in wakes behind single holes

Generic bench mark configurations

- **Example 4: Optically accessible IC-engine**
  - Different to GT-combustion there does not exist a simplified generic configuration where important and relevant effects can be studied!



Transparent DISI engine

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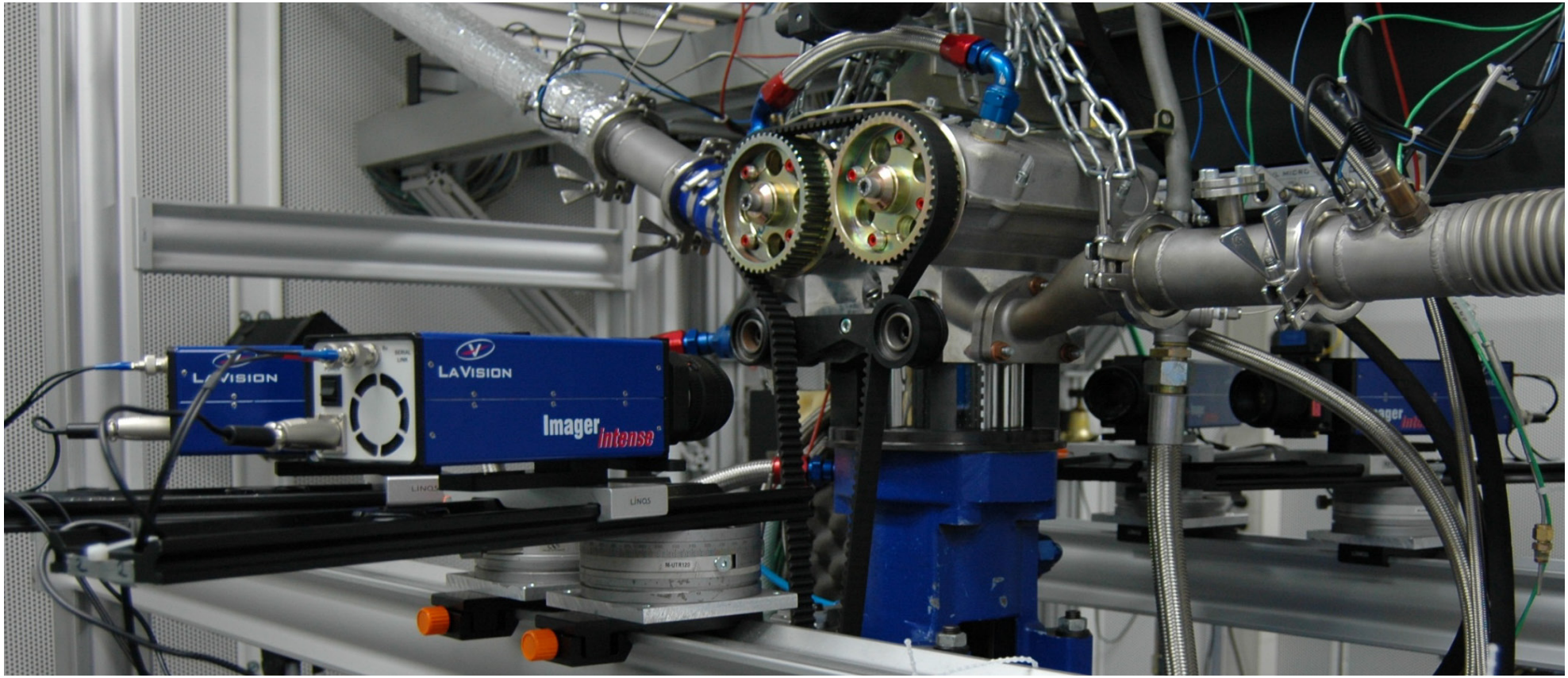
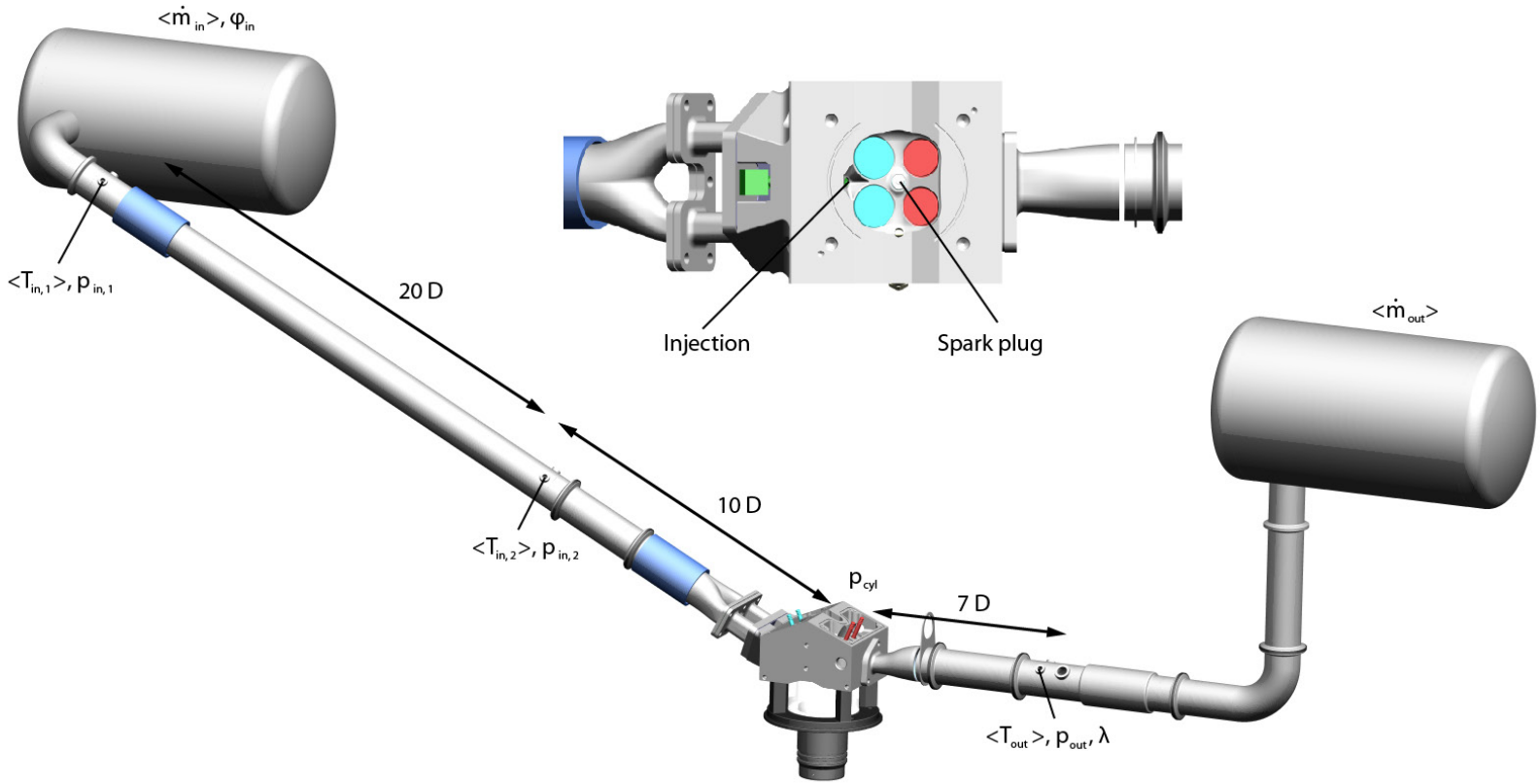


Boundary conditions



Specifications

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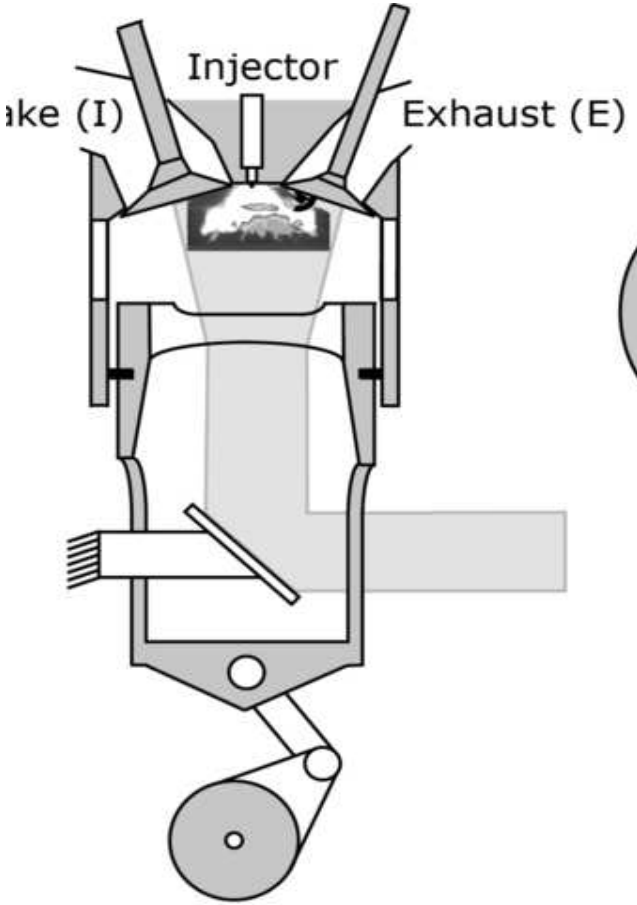
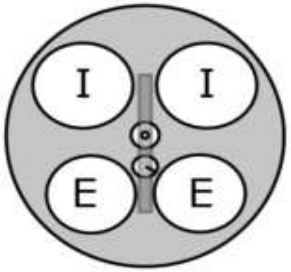
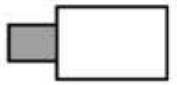
- **Optical accessible IC Engine**
  - Capacity: 499 ccm
  - Bore: 86 mm
  - Stroke: 86 mm
  - Compression ratio: 8.5
  - Optically accessible liner: 55 mm
- **Motored or fired operation:**
  - ≤ 3000 rpm
  - Manifold pressure: variable
- **Seeding**
  - Silicon oil (~1µm) or BN-particles

In-cylinder flow field measurements – 2C PIV

- **Particle Image Velocimetry (PIV)**
  - @ 16 kHz
  - 100 – 0 °bTDC
  - ~40x30mm²
  - 768x592px²
  - 273 cycles/run
- **<u>Challenges:</u>**
- **Scattered light off surfaces**
- **Contamination optical accesses**
- **Suitable PIV-seeding particles**
- **Optimized interval between laser illumination**







CMOS camera

In-cylinder flow field measurements – 2C PIV

- **Particle Image Velocimetry (PIV)**
  - @ 16 kHz
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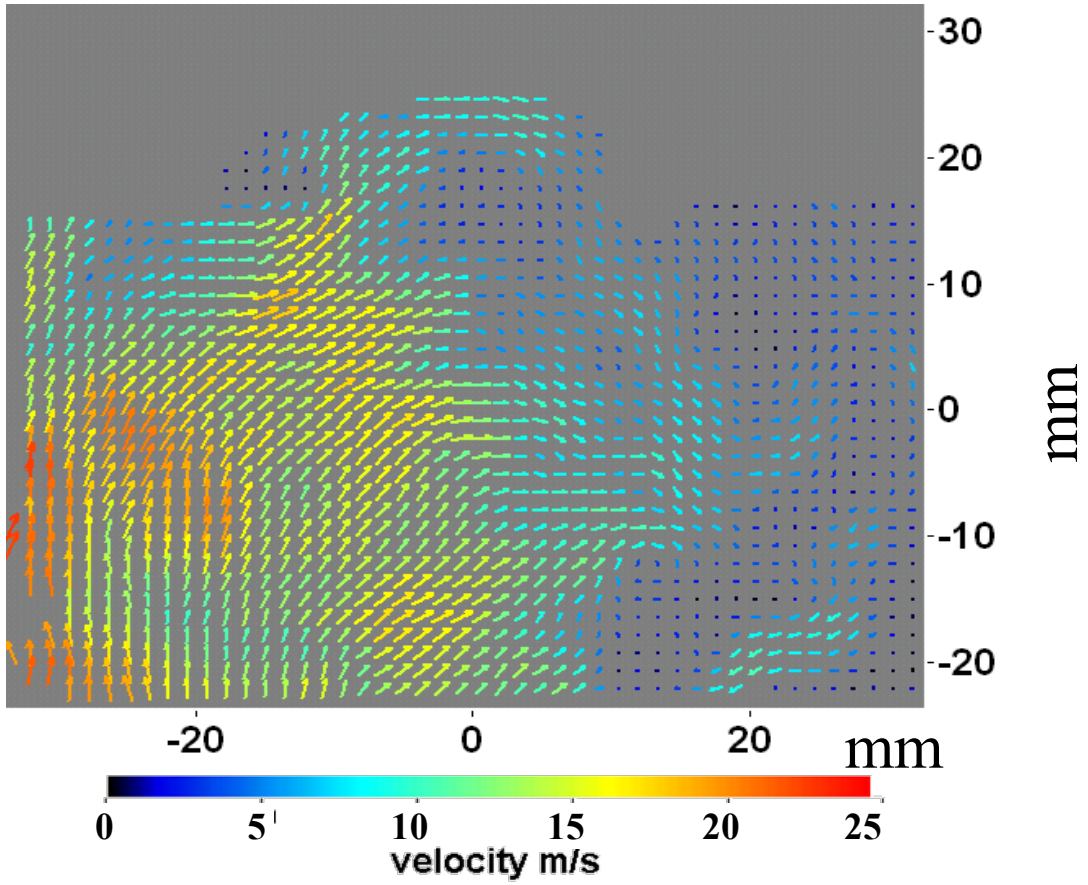
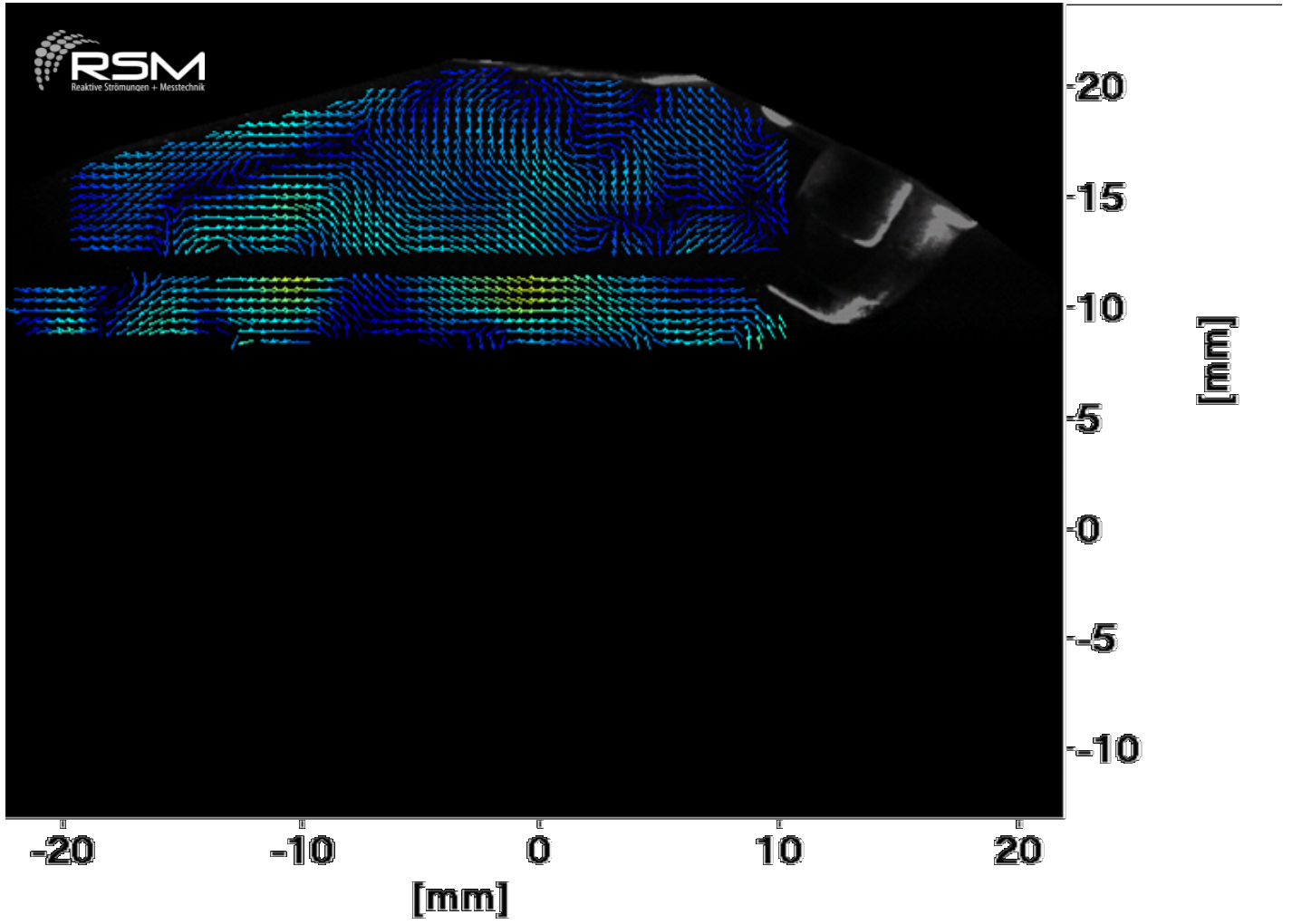
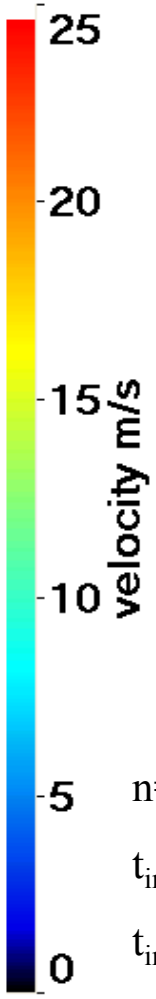


Stratified engine operation: Single cycle with double-injection





n=2000 min^{-1}

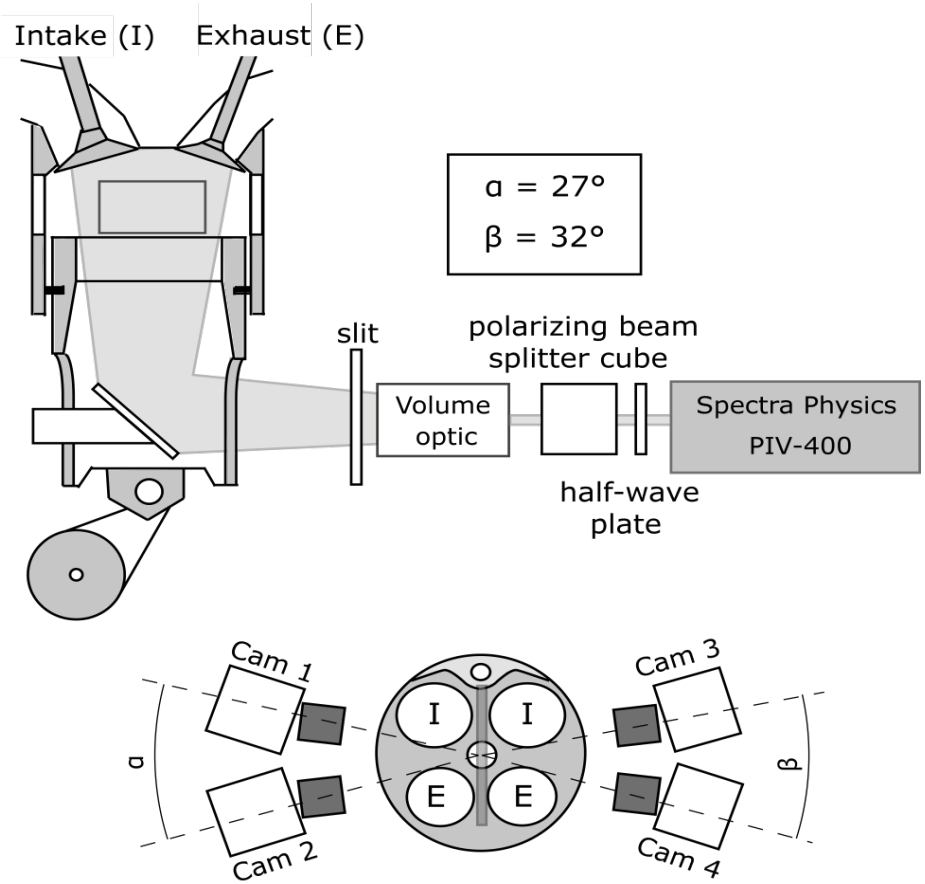
$t_{inj,1}$=190µs

$t_{inj,2}$=130µs

EOI= 28°bTDC

Towards volumetric imaging: example TomoPIV

- **Illumination**
  - Dual-cavity laser (PIV400, Spectra Physics)
  - Avg. 375 mJ per single pulse
  - Phase-locked acquisition during intake and compression (<5 Hz)
  - Volume of: 48 x 35 x 4/8 mm
- **Detection**
  - Interline transfer CCD (ImagerIntense, LaVision, 1376x1040 pixels)
  - Nikon 50 mm, 1.4 (f# 16)
  - Limitation of Camera angles due to cylinder head bolts

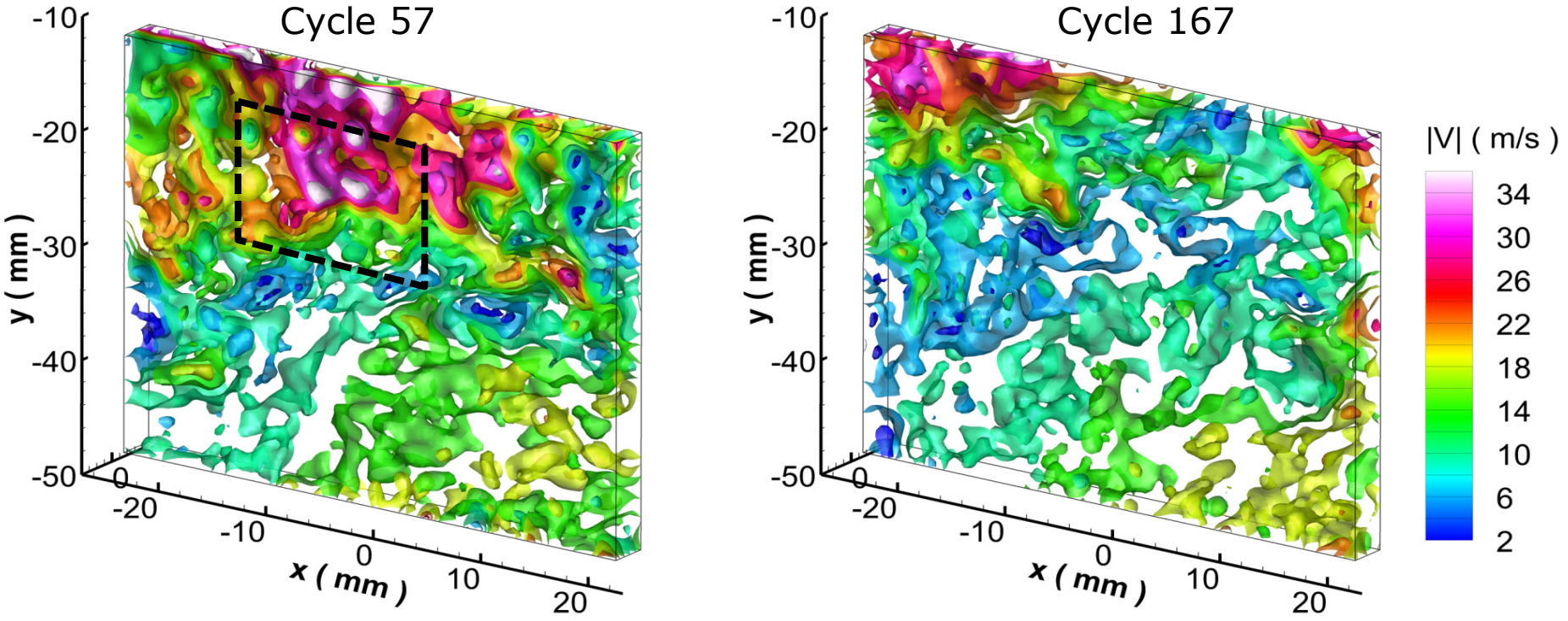


Instantaneous Results

- **Iso-surfaces of instantaneous velocity magnitudes**

Intake stroke (270° bTDC)

Δz = 4 mm



Baum et al. PCI 2013

Instantaneous Results

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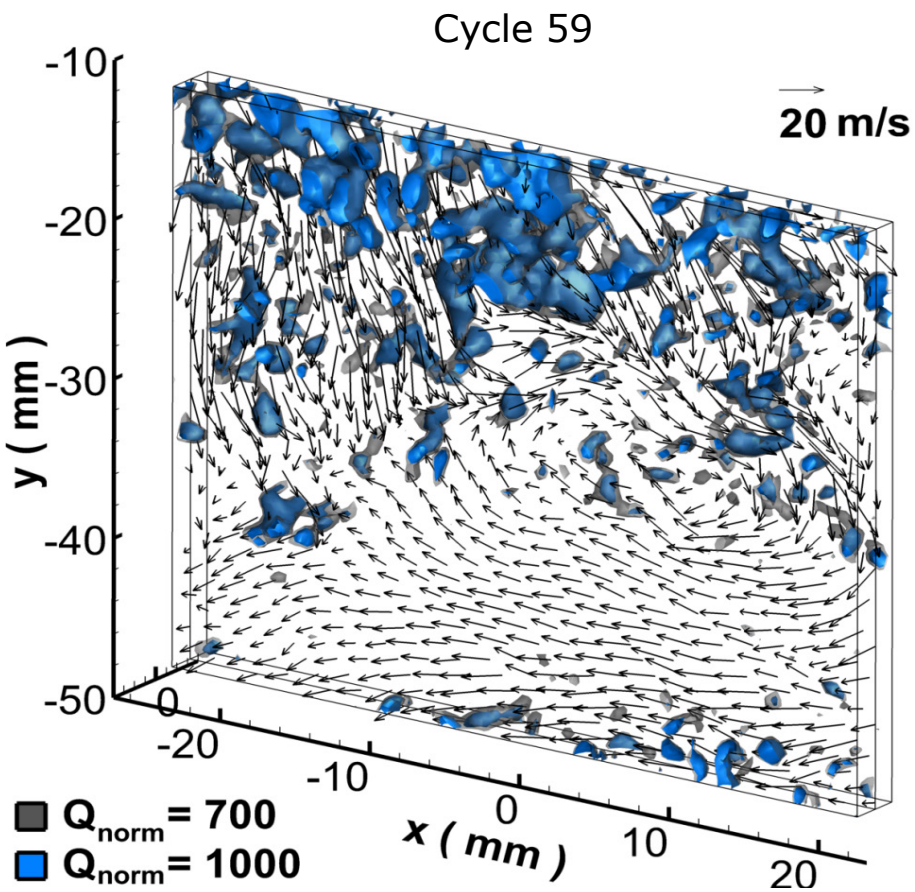
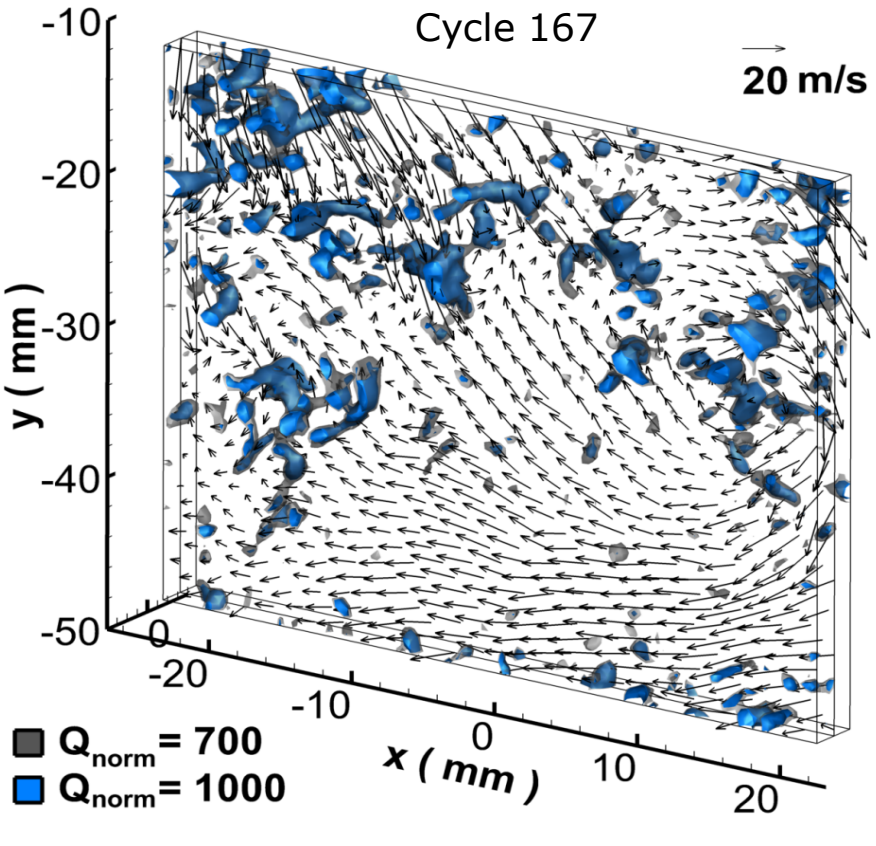
- Vortex region by second invariant of the velocity gradient tensor

Hunt et al., 1988: $Q_{incompresible} = \frac{1}{2}\left(|\Omega|^2 - |S|^2\right) \geq 0$; $Q_{norm} = \frac{Q_{incomp.} d^2}{|v|}$

d: bore; $|v|$:mean velocity





Conclusions – bench mark configurations

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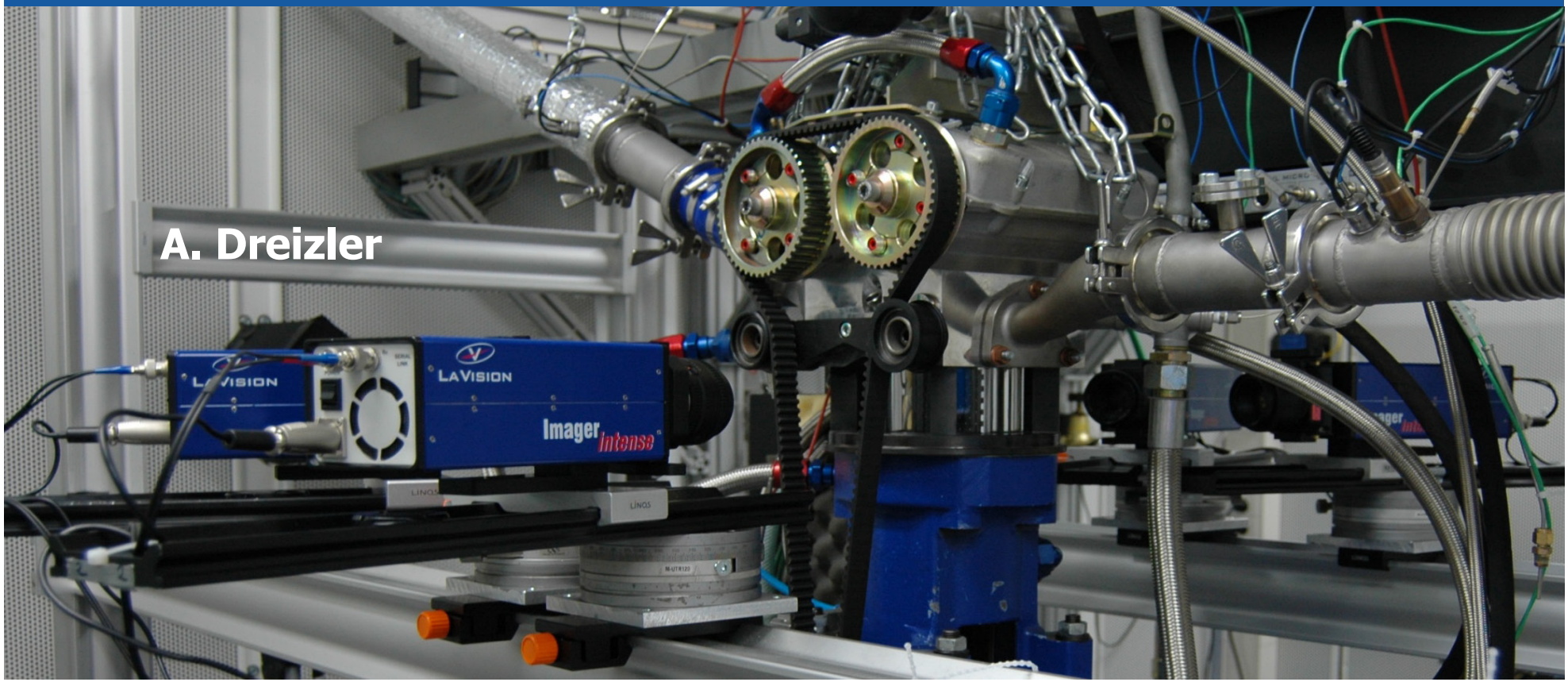
- Configurations of rising complexity and different geometries necessary to study different phenomena
- Optical access in atmospheric flames no problem
- Pressurized combustion (GT-combustor or IC-engine)
  - causes large investments for reliable, safe and reproducible operation
  - realization of optical access more difficult
- Improved characterization of inflow conditions needs more attention

Chapter 3: General Requirements for Laser Combustion Diagnostics

TU Darmstadt, Germany
Dept. of Mechanical Engineering
Institute for Reactive Flows and Diagnostics

A. Dreizler



Quantities of primary interest in combustion

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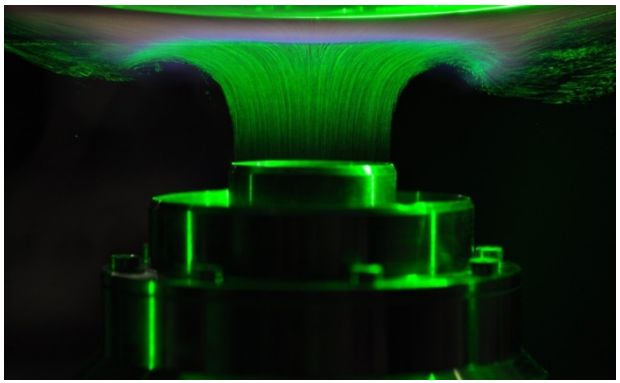
Methods from physics

⇩

Engineering sciences

Transfer of methods

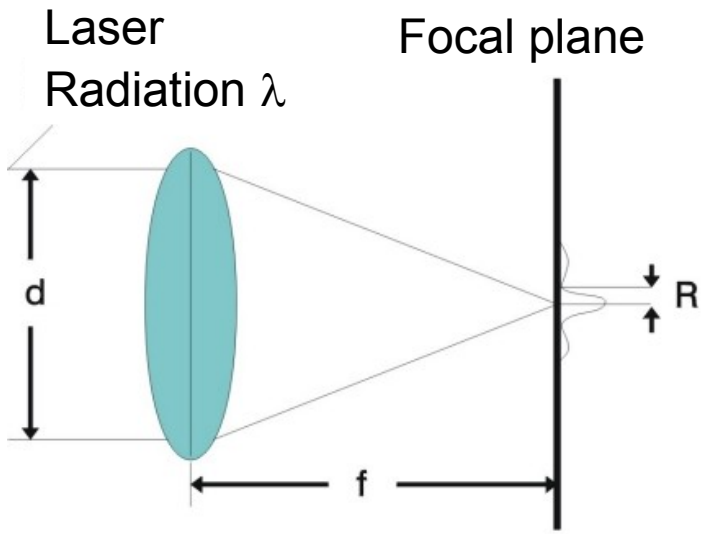
- Measuring by laser light
- Insitu-diagnostics → measuring inside combustors
- Non- or minimal intrusive
- High temporal resolution (~10^{-8}s)
- Reasonable spatial resolution (>10µm)



RSM Reaktive Strömungen + Messtechnik

Spatial resolution

- **Laser properties**
  - Coherent radiation → well focusable → small spot sizes = small probe volumes
  - For TEM_{00}-mode operation:



$$R = 1{,}22 \frac{f}{d} \lambda$$

  - Typical values f=350mm, d=10mm, λ=532nm

→ Spot size diameter 2R~45µm

  - In practice for pulsed lasers worse (~200µm)

Spatial resolution

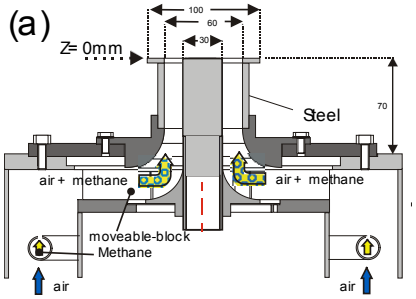
- **Typical spatial scales in turbulent flows**
  - Integral length scale $L_{ij,k}(\vec{x},t) = \frac{1}{2}\int_{-\infty}^{\infty} \rho_{ij}(\vec{x},t,r_k,0)dr_k$
  - Spatial covariance $\rho_{ij}(\vec{x},\vec{r},t) = \frac{\overline{u_i'(\vec{x},t)u_j'(\vec{x}+\vec{r},t)}}{\sqrt{\overline{u_i'^2}(\vec{x},t)}\sqrt{\overline{u_j'^2}(\vec{x}+\vec{r},t)}}$
  - Kolmogorov (smallest) length scale (ν kinematic viscosity m^2/s)

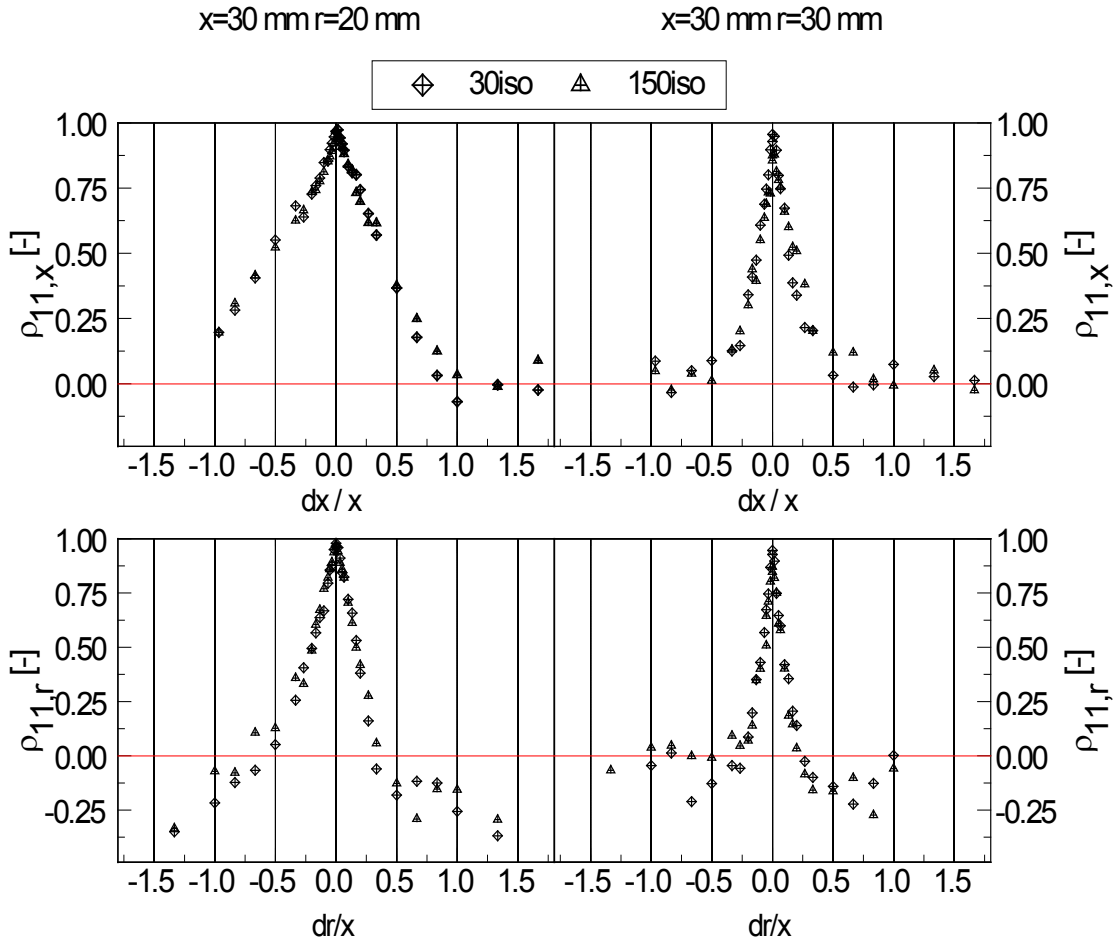
$$\eta_k = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4} \qquad \varepsilon = \frac{k^{\frac{3}{2}}}{L}$$

$$\eta_k = \frac{L}{Re_t^{0.75}} \qquad Re_t = \frac{k^{\frac{1}{2}}L}{\nu}$$

Spatial resolution

- **Full optical resolution:**
  2R (spot diameter) ≤ η_k (Kolmogorov scale)
- **Example non-reacting swirling flow**





30iso (Re=10000)
$L_{11,x}$=10mm

30iso (Re=10000)
$L_{11,r}$=6mm

⇨ η_k~50µm

Spatial resolution

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- **Comparison optical resolution and Kolmogorov scale**
  - Spot size **2R~45µm** (f=350mm, d=10mm, λ=532nm)
  - Kolmogorov scale η_k**~50µm** (swirled air flow at Re=10000)
  - → Same order of magnitude but in practice often not fully resolved

→ **To be considered when comparing experimental data to numerical results**

  - Smoothing of measurands is an important issue but not yet any commonly agreed advice for best practice when comparing "filtered" measurands with "filtered" quantities from CFD

Temporal resolution

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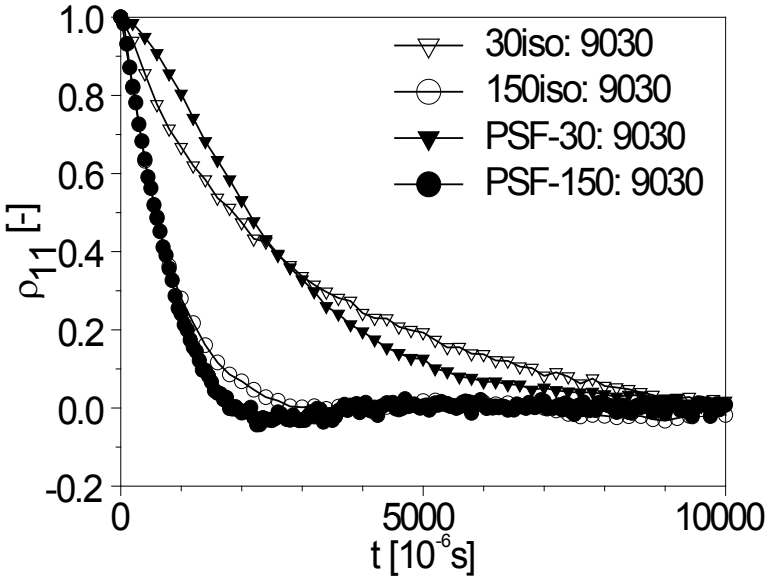
- **Pulsed laser operation**
  - Quality (q-) switch allows ns-pulses (10^{-9} s)
  - 1ns pulse corresponds to ~30cm
  - Pulsed operation increases intensity dramatically → non-linear optical methods become feasible (most prominent method CARS)
- **Typical time scales in turbulent flames**
  - Integral time scale $T_{ij}(\vec{x},t) = \frac{1}{2}\int_{-\infty}^{\infty} \rho_{ij}(\vec{x},t,0,\tau)d\tau$
  - Temporal auto-covariance $\rho_{ij}(\vec{x},t,0,\tau) = \frac{\overline{u_i'(\vec{x},t)u_j'(\vec{x},t+\tau)}}{\sqrt{\overline{u_i'^2}(\vec{x},t)}\sqrt{\overline{u_j'^2}(\vec{x},t+\tau)}}$
  - Kolmogorov time scale $\tau_k = \left(\frac{\nu}{\varepsilon}\right)^{1/2}$

$$\varepsilon = \frac{k^{\frac{3}{2}}}{L}$$

Temporal resolution

- **Example reacting swirling lean premixed flame**



PSF-30 (Re=10000)
T=1.2ms

⇨ τ_k~170µs

- **Comparison optical resolution and Kolmogorov time scale**
  - Laser pulses are much shorter than any time scales in turbulent flames
  - Temporal resolution is no problem

  → Comparison of calculated and measured power spectra better in frequency domain

0D – 3D measurements by laser diagnostics

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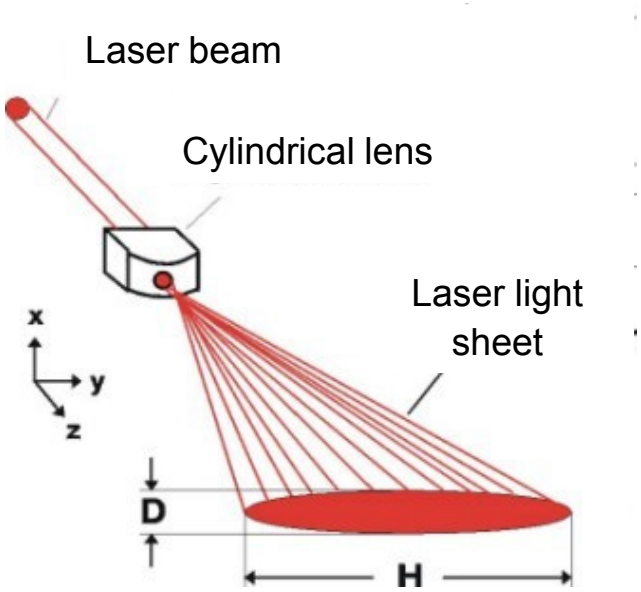
- **Up to 3 spatial dimensions are observable**
  - 0D/ 1D: generation of a thin laser beam
  - 2D: generation of a laser light sheet



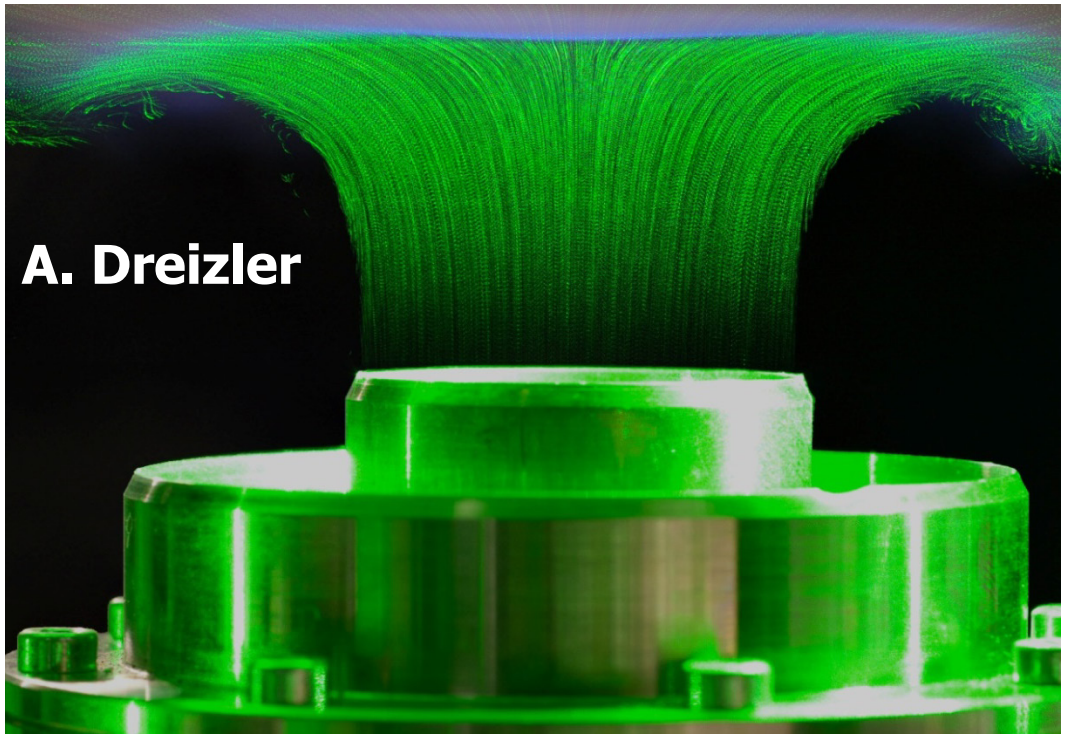
  - (Quasi-)3D: multiple and parallel laser light sheets
  - Extension to cinematographic (quasi-)3D imaging

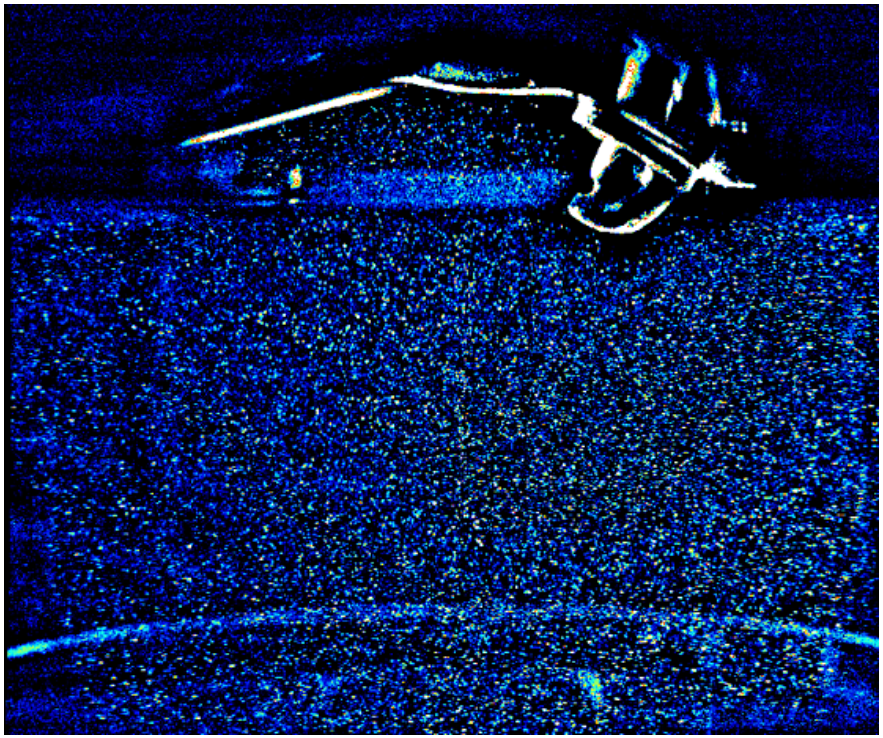
Chapter 4:
Particle-Based Velocimetry

TU Darmstadt, Germany
Dept. of Mechanical Engineering
Institute for Reactive Flows and Diagnostics

TECHNISCHE UNIVERSITÄT DARMSTADT

RSM
Reaktive Strömungen + Messtechnik

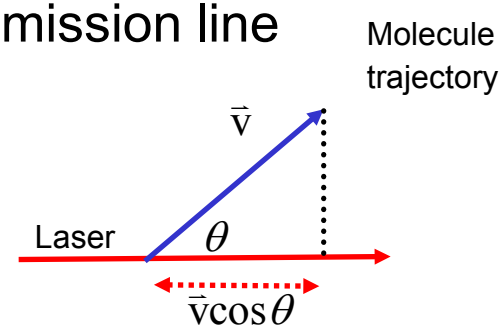


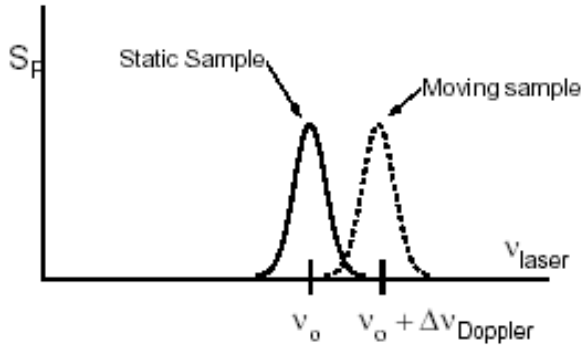


Flow field measurements

- **Spectroscopic methods**
  - Doppler-shift of absorption/ emission line

$$\Delta\nu_{\text{Doppler shift}} = \frac{\vec{v}\cos\theta}{\lambda}$$





  - **NOT discussed here**

- **Particle based methods**
  - Doppler shift during Mie scattering process (Laser Doppler Velocimetry, LDV, using heterodyne technique)
  - Sequential exposures of instantaneous particle positions by Mie scattering (Particle Image Velocimetry, PIV)

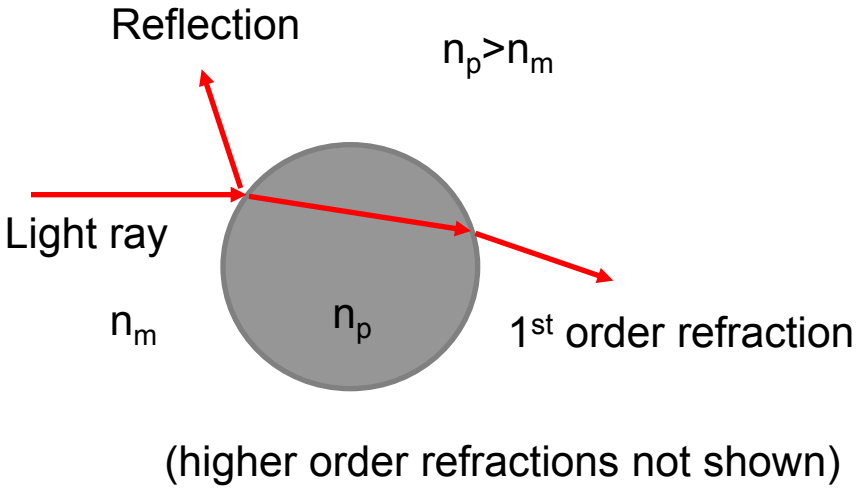
Particle-based flow field measurements

Mie scattering:

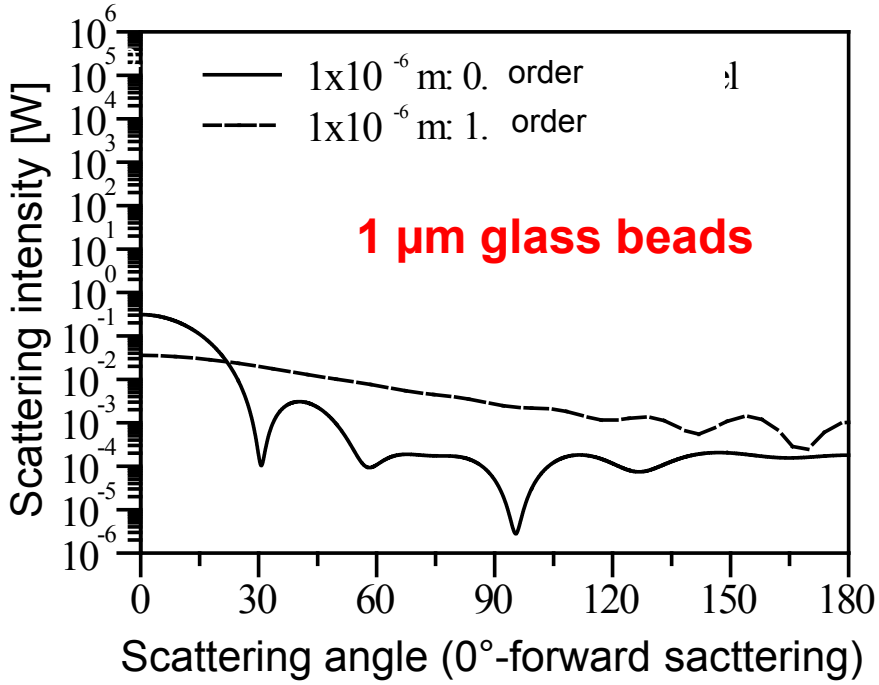
Scattering of electro-magnetic waves off spherical particles

Particle-based flow field measurements

- **Mie scattering: spherical particles seeded to the flow**
  - Intensity of Mie scattered light in dependence of scattering angle
  - Example: transparent glass bead, 1µm diameter



(higher order refractions not shown)



  - Forward scattering highest intensities
  - Use of Mie scattering for tracking gas velocities

Particle-based flow field measurements

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- **Seeding material for turbulent flame research**
  - Chemically inert
  - Melting point exceeding adiabatic flame temperatures (>2500K), oil droplets as in aerodynamic studies often not feasible
  - Sufficiently small to reduce slip *s* between particle (u_p) and gaseous fluid (u_f)

$$s = \left| \frac{u_f - u_p}{u_f} \right| \overset{!}{<} 1\%$$

  - Cut-off frequency exceeding slip of 1%

$$f_c = \frac{\sqrt{\left(2s - s^2\right)}}{2\pi\tau_0 \sqrt{\left(1 - s^2\right)\left(1 + \frac{\rho_f}{2\rho_p}\right)^2 - \left(\frac{3\rho_f}{2\rho_p}\right)^2}}$$

$$\tau_0 = \frac{\rho_P d_P^2}{18\eta} \qquad \eta: \text{ dynamic viscosity}$$

Particle-based flow field measurements

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- **Typical seeding materials**

Material	Short notation	Density [kg/m^3]	Melting point [K]
Magnesium oxide	MgO	3500	2800
Zirconium silicate	$ZrSiO_4$	3900 - 4700	2420
Titanium dioxide	TiO_2	4000	1780

Particle-based flow field measurements

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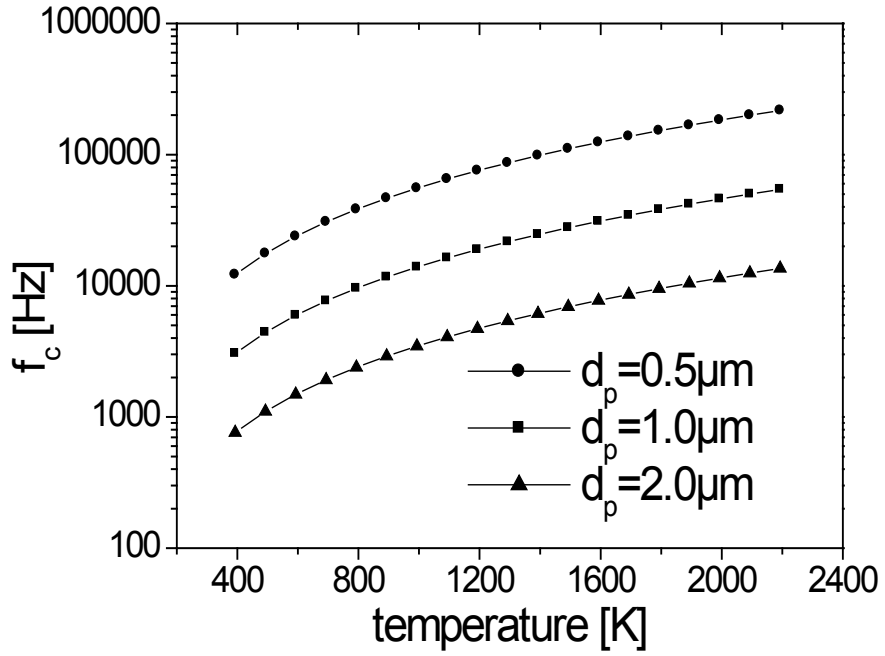
- **Example**
  - MgO
  - f_c: maximal turbulent fluctuations that can be resolved, slip < 1%



→ Smaller particles and higher viscosity (higher T) expand the range of resolvable velocity fluctuations

→ <u>But</u>: Mie signal decrease nonlinearly with decreasing particle size

Particle-based flow field measurements

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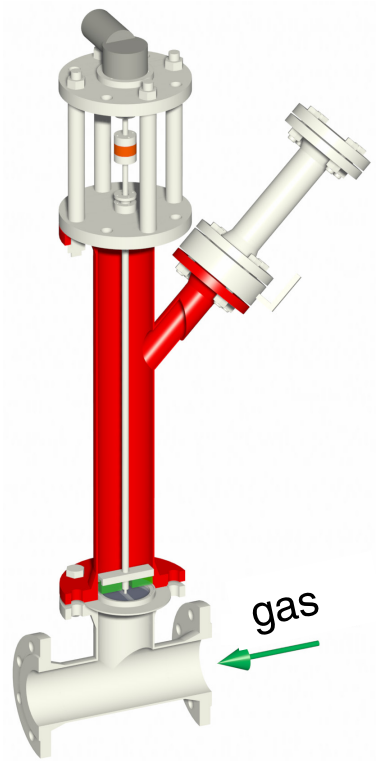
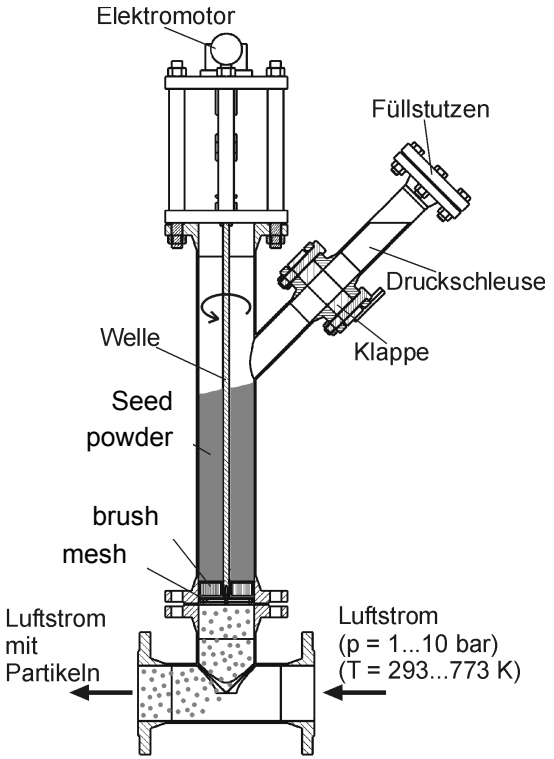
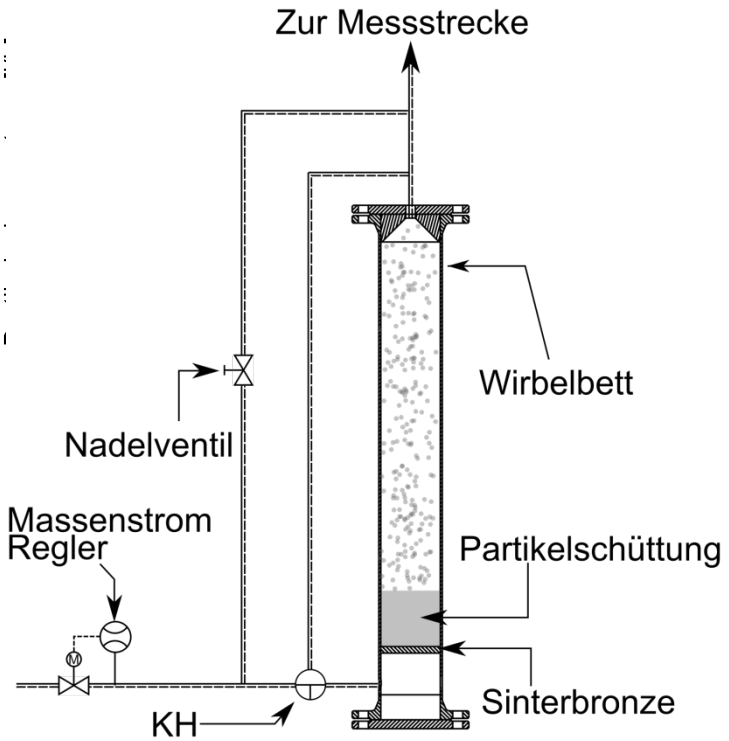
- **Addition of seed material to the flow**
  - All gas feeds must be seeded, **otherwise results can be biased**
  - Volume fraction of seed material must be variable
    - Bypass, controlled and variable mass flow
    - Appropriate assembly for addition of seed (“seeding-generator”)

Rotating brush



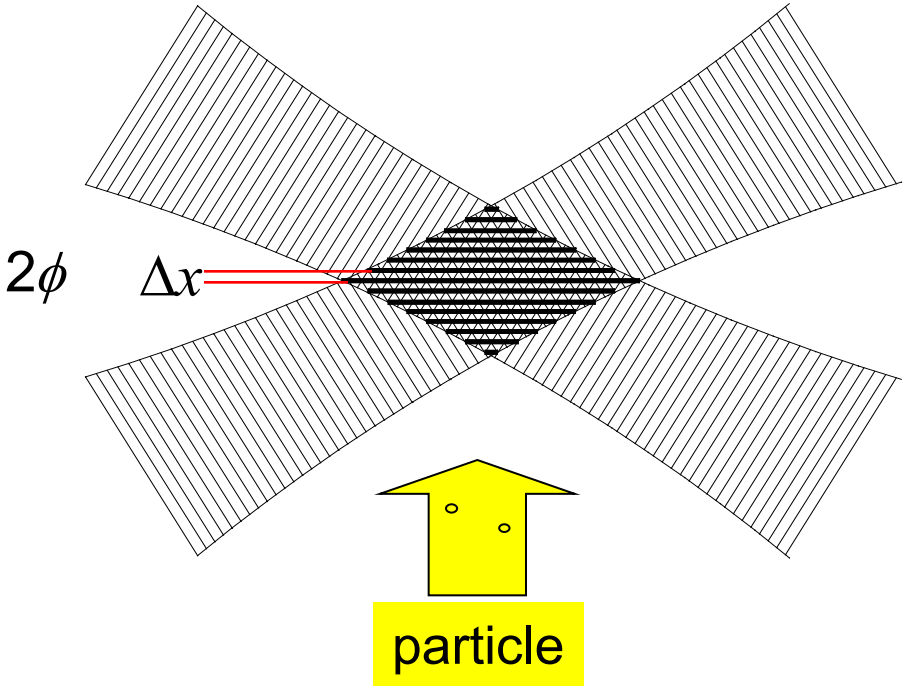


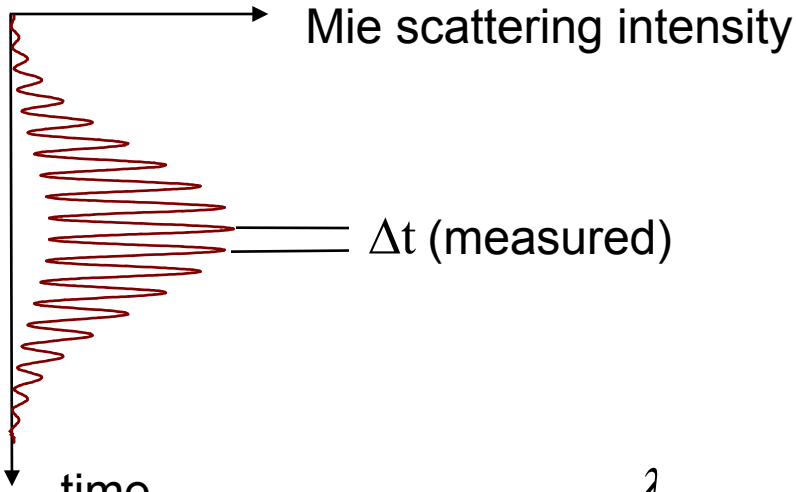
Fluidised bed



Laser Doppler Velocimetry

- **Principle**
  - Pictorial explanation, correct derivation in text books





$$\Delta x = d_{fringes} = \frac{\lambda_{laser}}{2\sin\phi}$$

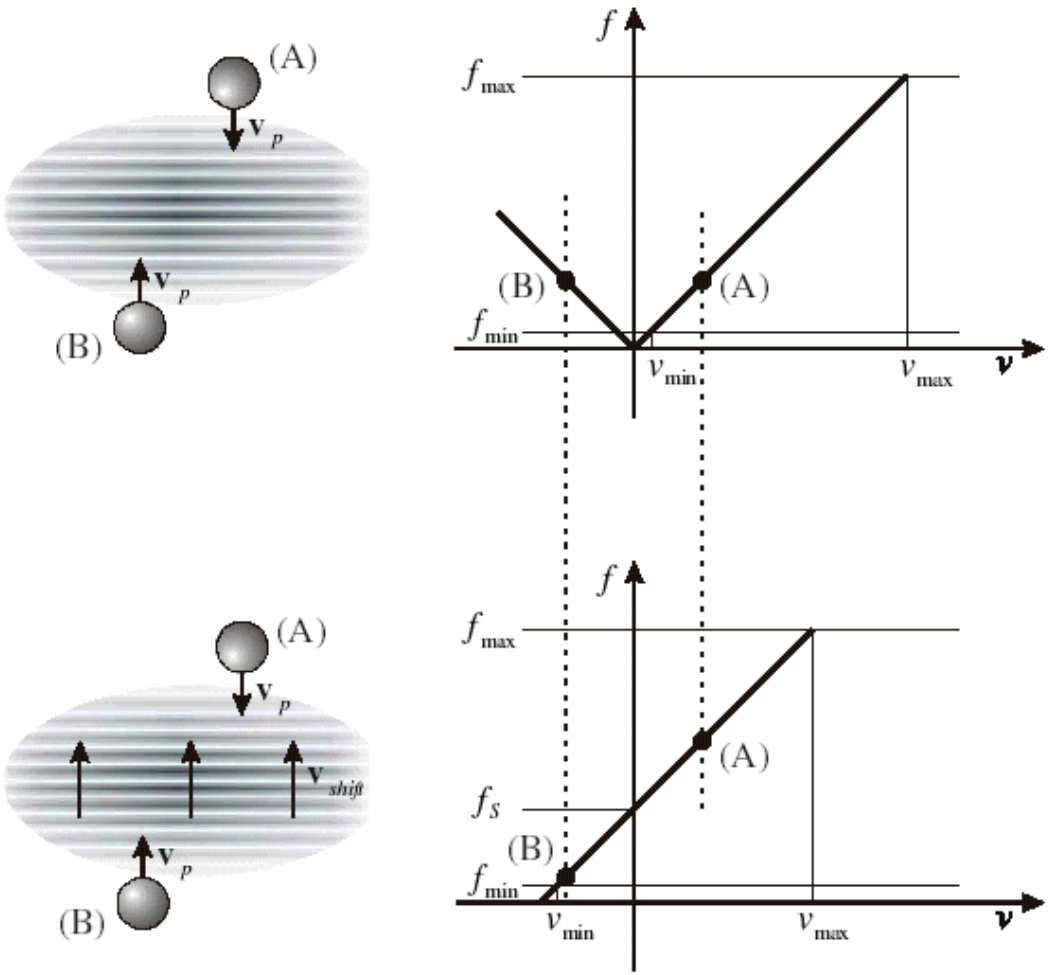
$$\Rightarrow \quad \left|\vec{v}_{\perp \text{Interference pattern}}\right| = \frac{\text{distance between stripes}}{\text{particle flight time}} = \frac{\Delta x}{\Delta t}$$

$\Rightarrow$ Instantaneous velocity, temporal resolution ~µs

Laser Doppler Velocimetry

- **Measurement of absolute values = ambiguity in direction**

→ **Use of moving interference stripes (generated by Bragg cell, phonon-photon interaction, crossing laser beams slightly different frequency, difference ~ 40 MHz)**



Laser Doppler Velocimetry

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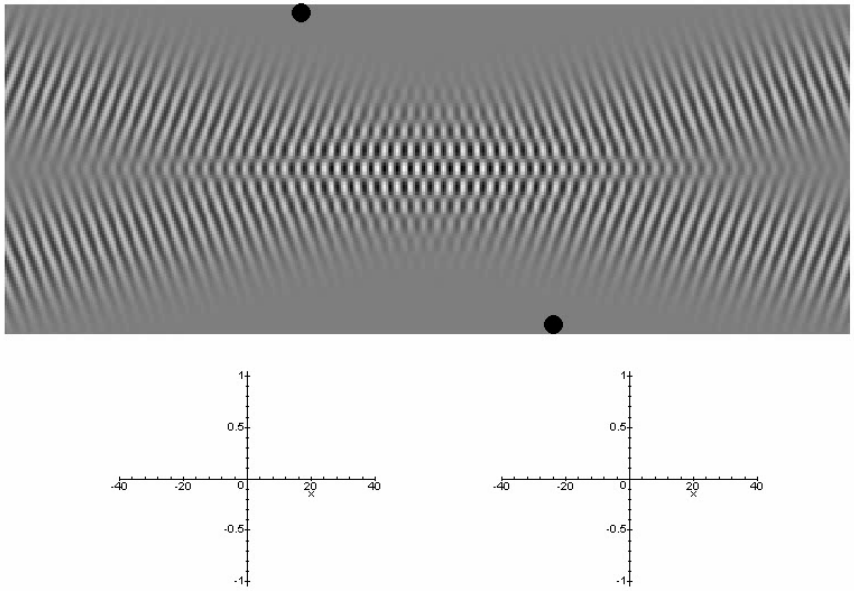
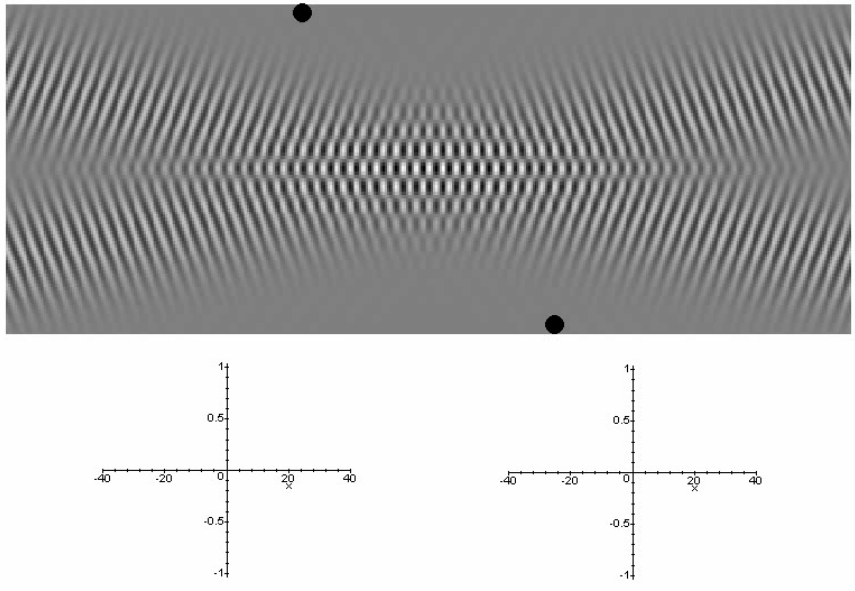
Without shift

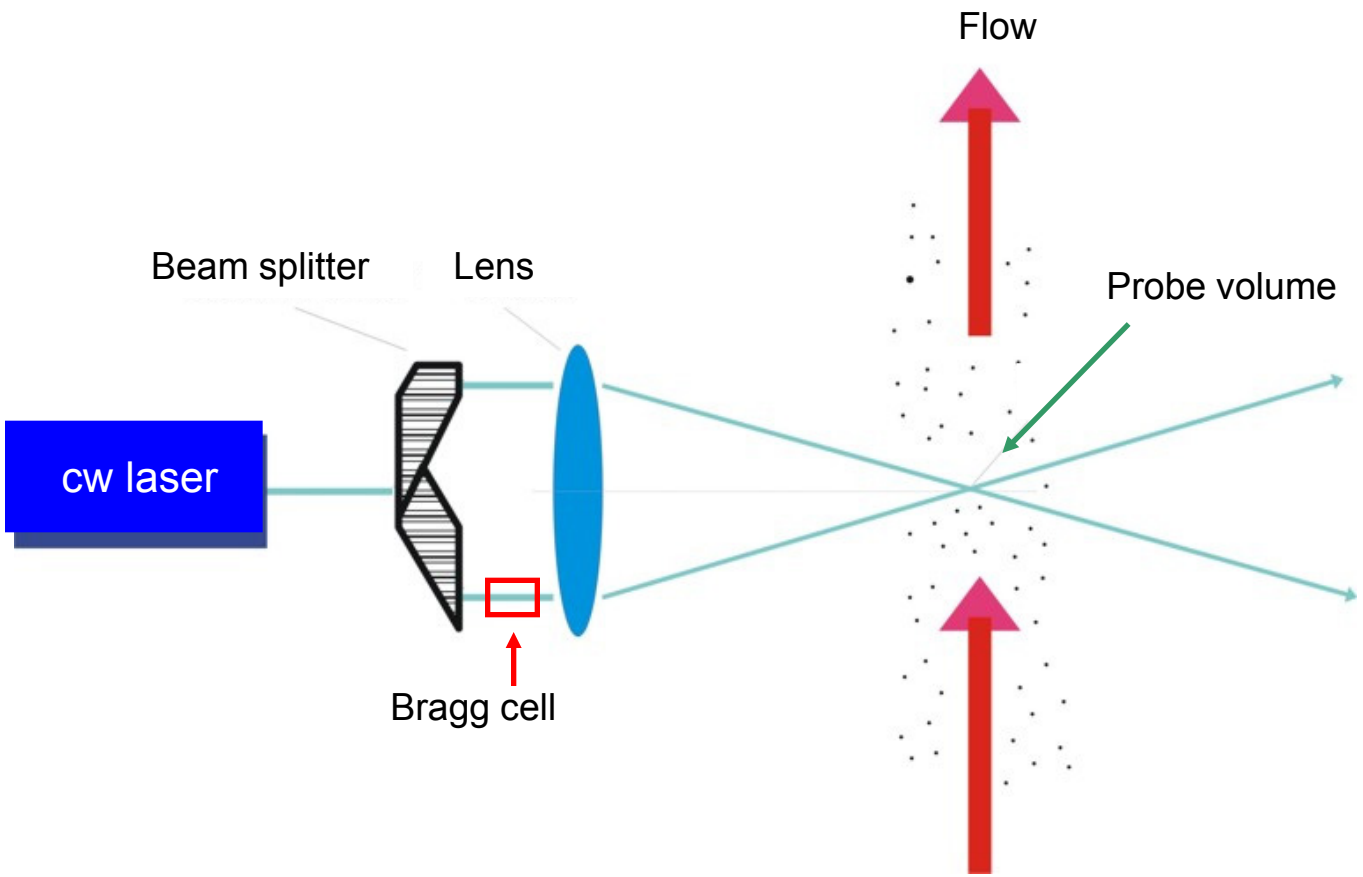


With shift



Laser Doppler Velocimetry

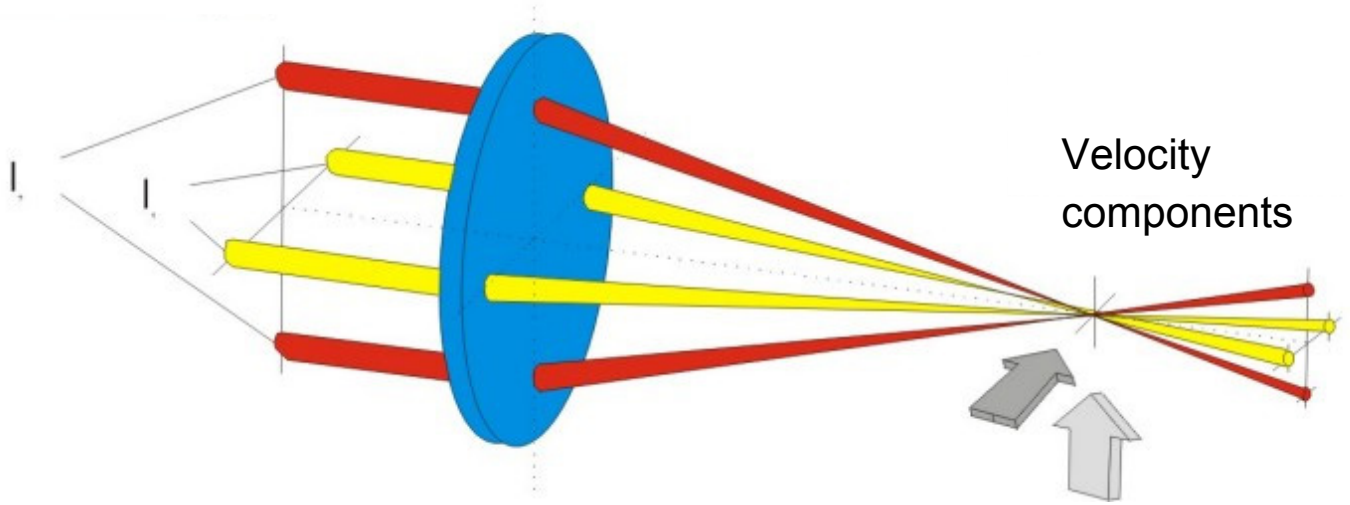
- **Practical realization**
  - Continuous wave (cw) laser: argon ion laser, DPSS laser



Bragg-cell: generates a moving interference pattern

Laser Doppler Velocimetry

- **Two velocity component measurement**
  - Two colors from argon ion laser
  - Two photomuliplier tubes equipped with interference filters



Laser Doppler Velocimetry

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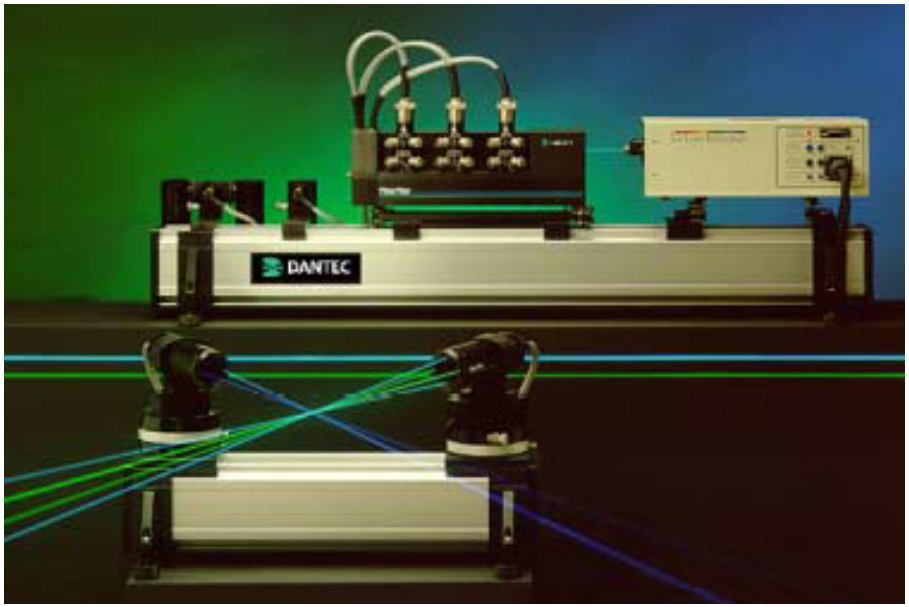
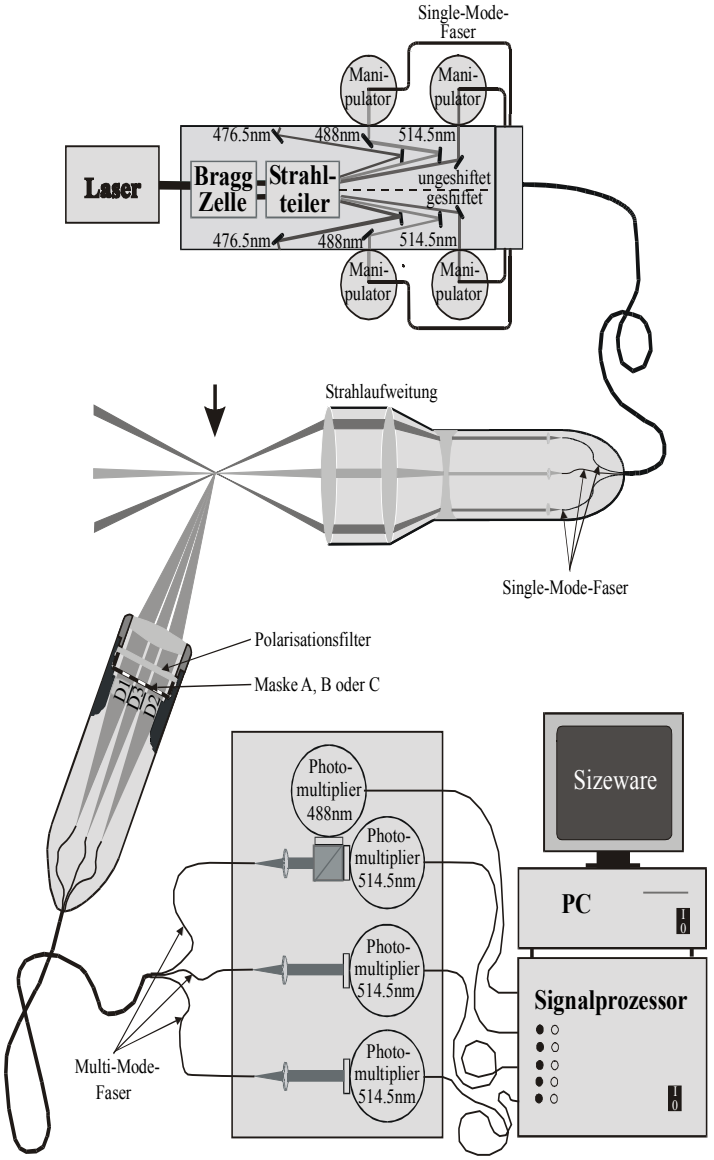
- **Commercial setup**
  - Optical fibres
  - Simple alignment





Laser Doppler Velocimetry

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- **Single-point, 2-component LDV: measuring single point statistical moments**
- **Data base consisting of statistically uncorrelated data**
  - Mean velocity
    - t_i: transit time, weighting by t_i to avoid bias by "fast particles"

$$\overline{u} = \frac{\sum_{i=1}^{N} u_i \cdot t_i}{\sum_{i=1}^{N} t_i}$$

  - Velocity variance

$$\left\langle u'^2 \right\rangle = \frac{\sum_{i=1}^{N} u_i'^2 \cdot t_i}{\sum_{i=1}^{N} t_i}$$

  - Standard deviation, root-mean-square

$$\sigma_u = \sqrt{\left\langle u_i'^2 \right\rangle}$$

  - Turbulent kinetic energy (axisymmetric)

$$k = \tfrac{1}{2} \left(\sigma_u^2 + 2 \cdot \sigma_v^2 \right)$$

  - Reynolds stresses

$$\left\langle u'v' \right\rangle = \frac{\sum_{i=1}^{N} u_i' \cdot v_i' \cdot t_i}{\sum_{i=1}^{N} t_i}$$

Laser Doppler Velocimetry

- **Single-point, 1-component LDV (→ for higher data rates): Measuring two-point statistics**
- **Data base consisting of time-series (statistically correlated)**
  - Temporal covariance: $\Delta x=0$, i=j

$$R_{ij}\left(\vec{x},\Delta x,t,\Delta t\right)=\overline{u_i'\left(\vec{x},t\right)u_j'\left(\vec{x}+\Delta x,t+\Delta t\right)}$$

  - Integral time scale

$$T_{ij}\left(\vec{x},t\right)=\frac{1}{2\overline{u_i'\left(\vec{x},t\right)u_j'\left(\vec{x}+\Delta\vec{x},t+\Delta t\right)}}\int_{-\infty}^{\infty}R_{ij}\left(\vec{x},t,0,\Delta t\right)d\left(\Delta t\right)$$

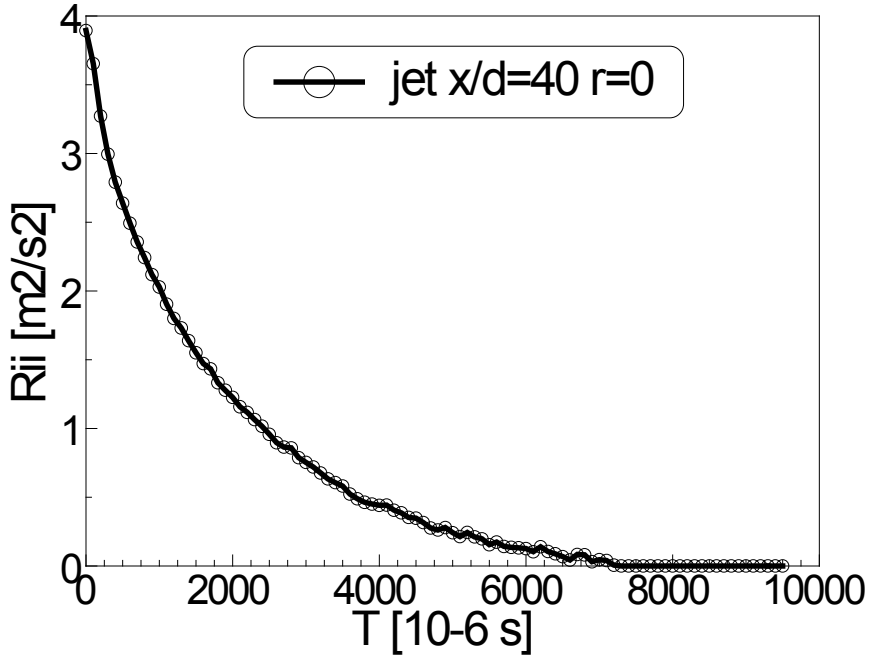
  - Power spectral density

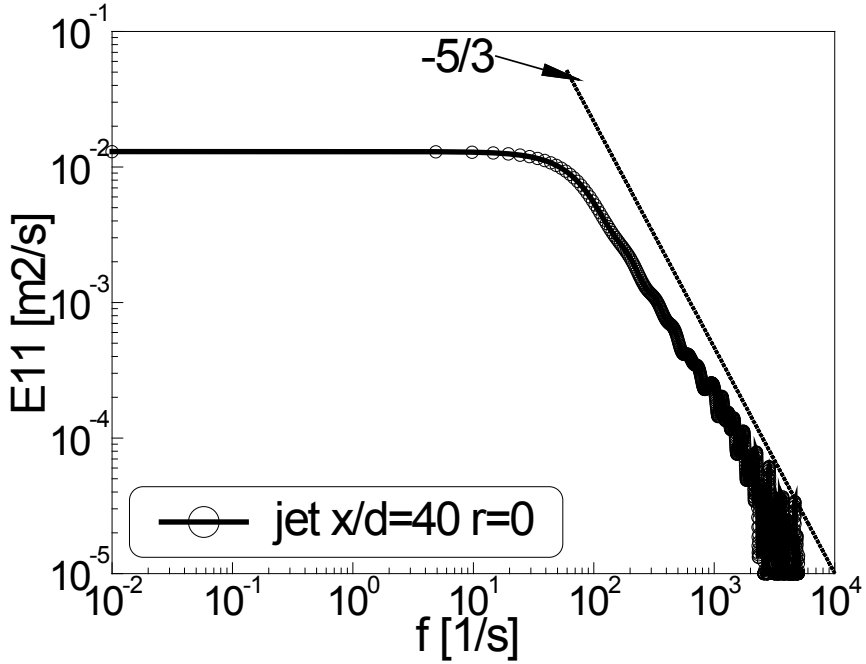
$$\Psi_{ij}\left(\vec{x},\kappa,t\right)=\frac{1}{\left(2\pi\right)^3}\int_{-\infty}^{\infty}\exp\left(-i\vec{\kappa}\Delta\vec{x}\right)R_{ij}\left(\vec{x},\Delta\vec{x},t\right)d\left(\Delta\vec{x}\right)$$

Laser Doppler Velocimetry

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Single-point, 1-component LDV: Measured variables**
- **Example isothermal jet**





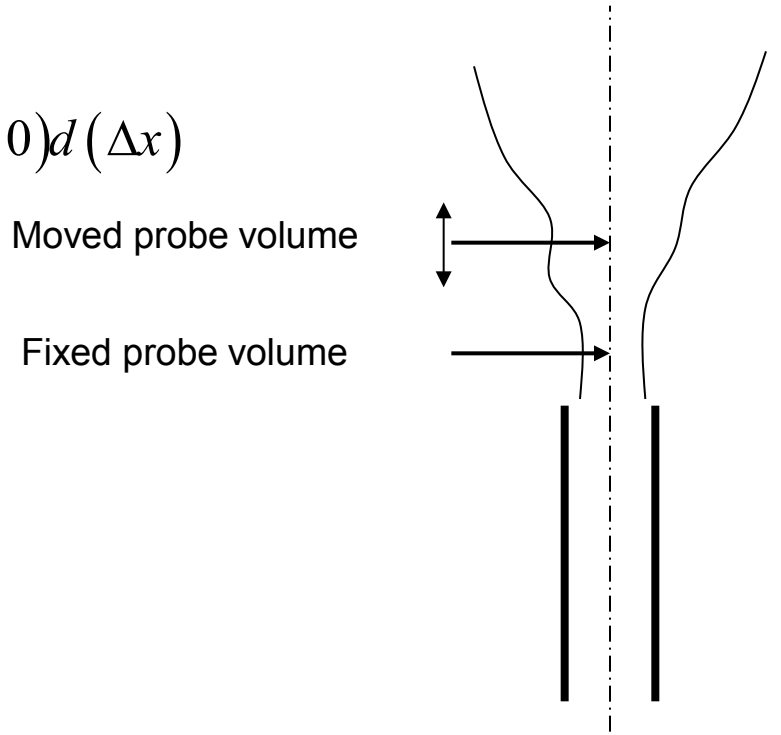
Laser Doppler Velocimetry

- **Two-point, 1-component LDV: Measuring spatial two-point correlations**
- **Data base consisting of time-series**
  - Spatial covariance: $\Delta t=0$

$$R_{ij}\left(\vec{x},t,\Delta\vec{x},\Delta t\right)=\overline{u_i'\left(\vec{x},t\right)u_j'\left(\vec{x}+\Delta\vec{x},t+\Delta t\right)}$$

  - Integral length scale

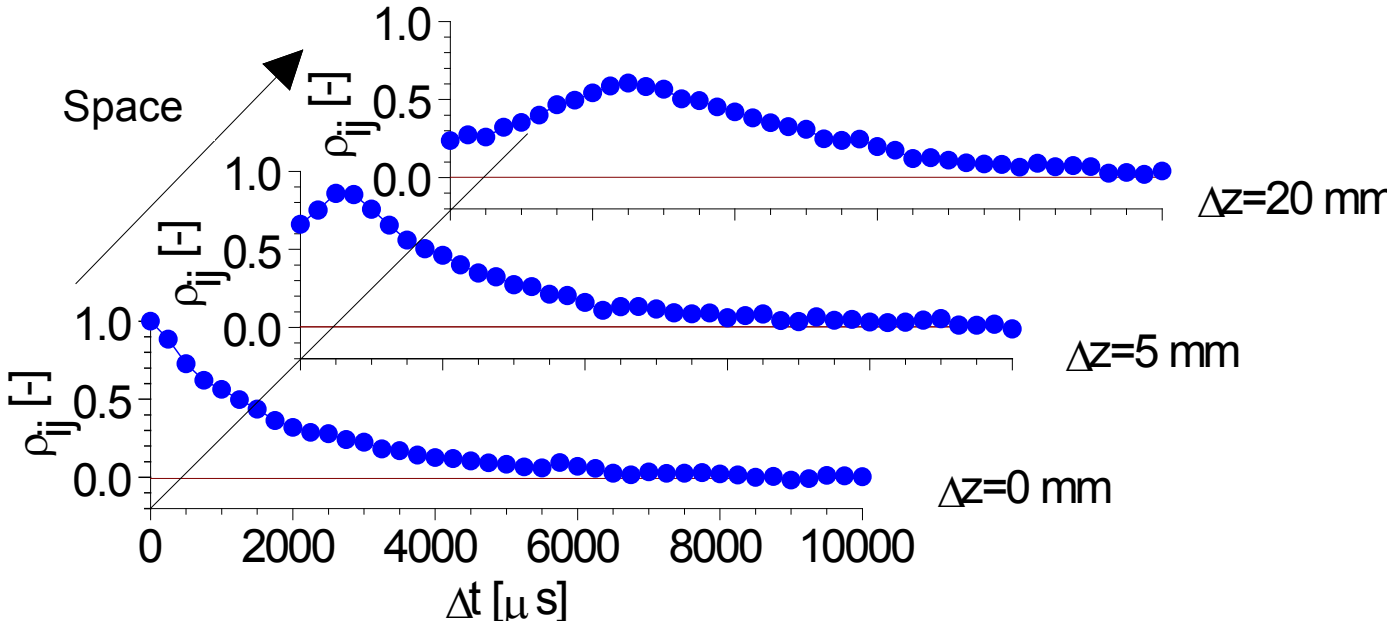
$$L_{ij}\left(\vec{x},t\right)=\frac{1}{2u_i'\left(\vec{x},t\right)u_j'\left(\vec{x}+\Delta\vec{x},t\right)}\int_{-\infty}^{\infty}R_{ij}\left(\vec{x},t,\Delta\vec{x},0\right)d\left(\Delta x\right)$$



Laser Doppler Velocimetry

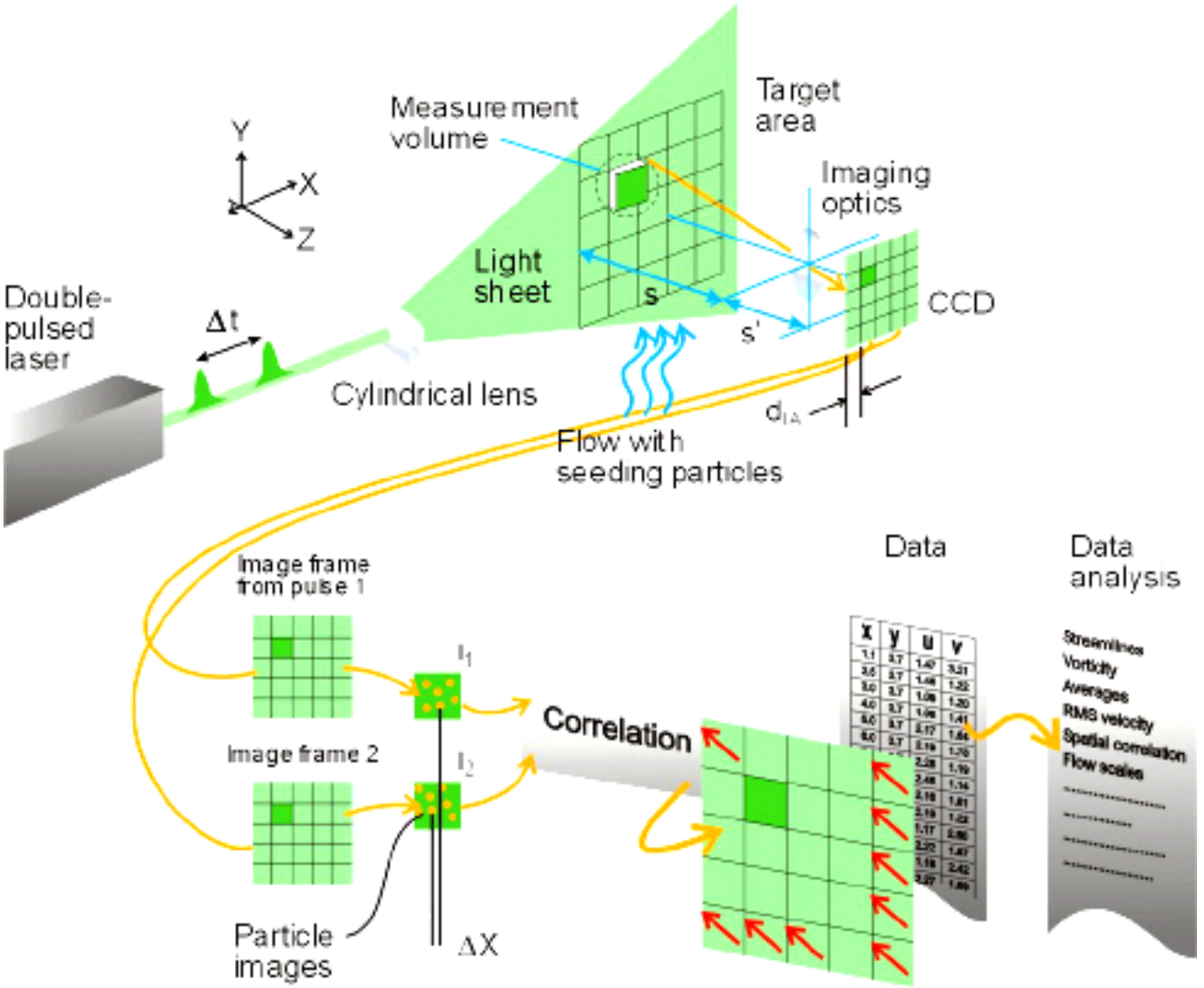
- **Two-point, 1-component LDV**
- **Example: Isothermal jet, time-space correlation**

$$\rho_{ij}(\vec{x},t,\Delta z,\Delta t)=\frac{\overline{u_i'(\vec{x},t)u_j'(\vec{x}+\Delta z,t+\Delta t)}}{\sqrt{\overline{u_i'^2(\vec{x},t)}\cdot\ \overline{u_j'^2(\vec{x}+\Delta z,t+\Delta t)}}}$$



Particle Image Velocimetry

- **Principle**



Source: LaVision

Particle Image Velocimetry

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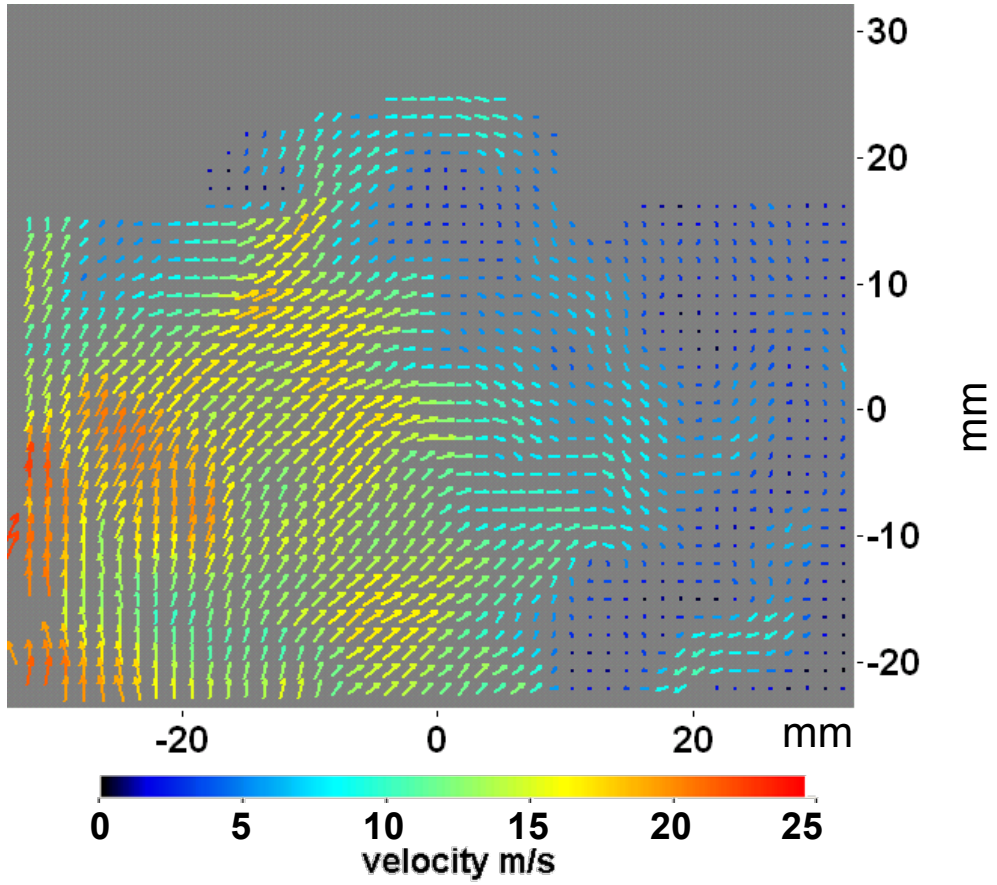
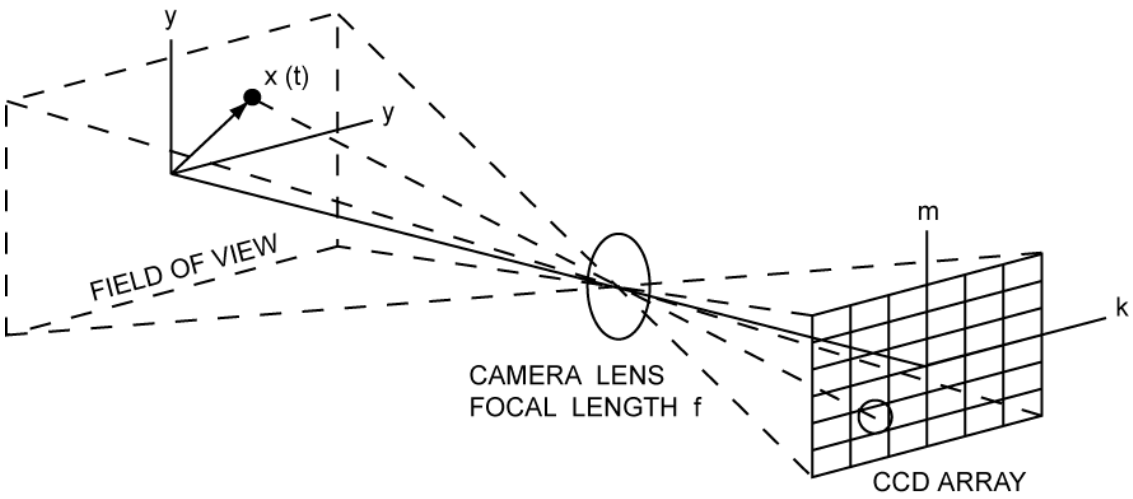
- **Movie of particles in IC engine**



Particle Image Velocimetry

- **Imaging**

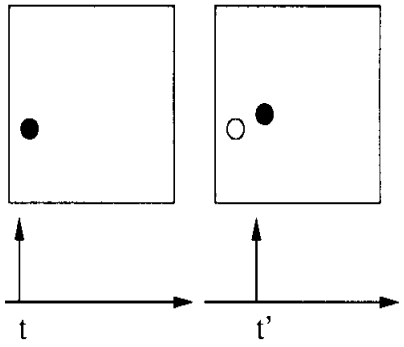


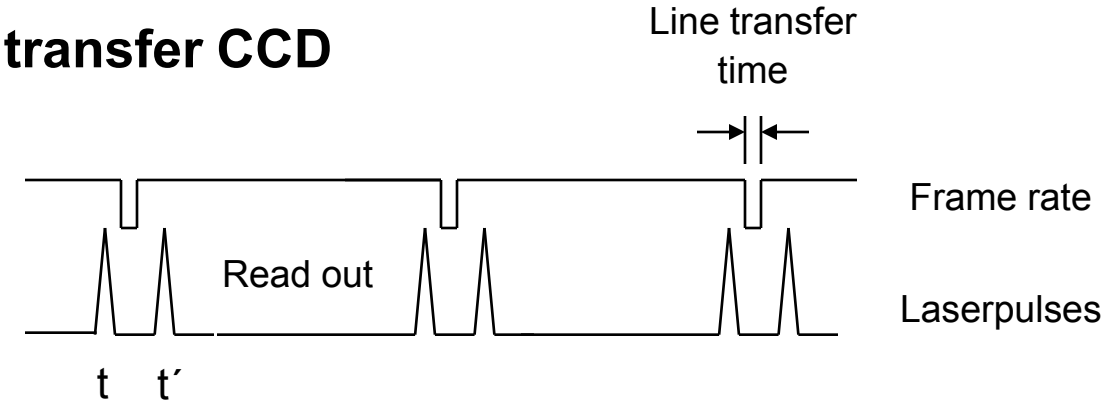
! Calibration required !

Pixel → mm-scale

Calibration target required

- **Full-frame interline transfer CCD**

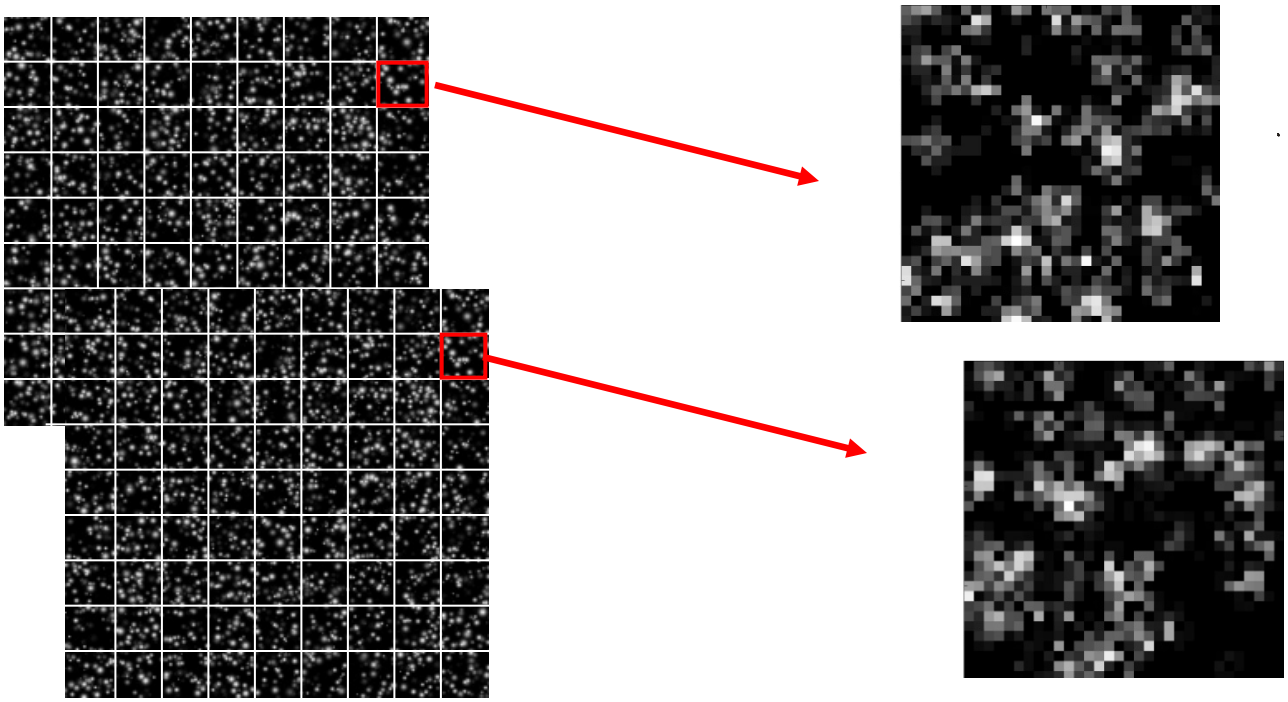




Particle Image Velocimetry

- **Cross-correlation**

Frame 1: $t = t_0$



Frame 2: $t = t_0 + \Delta t$

Full frame

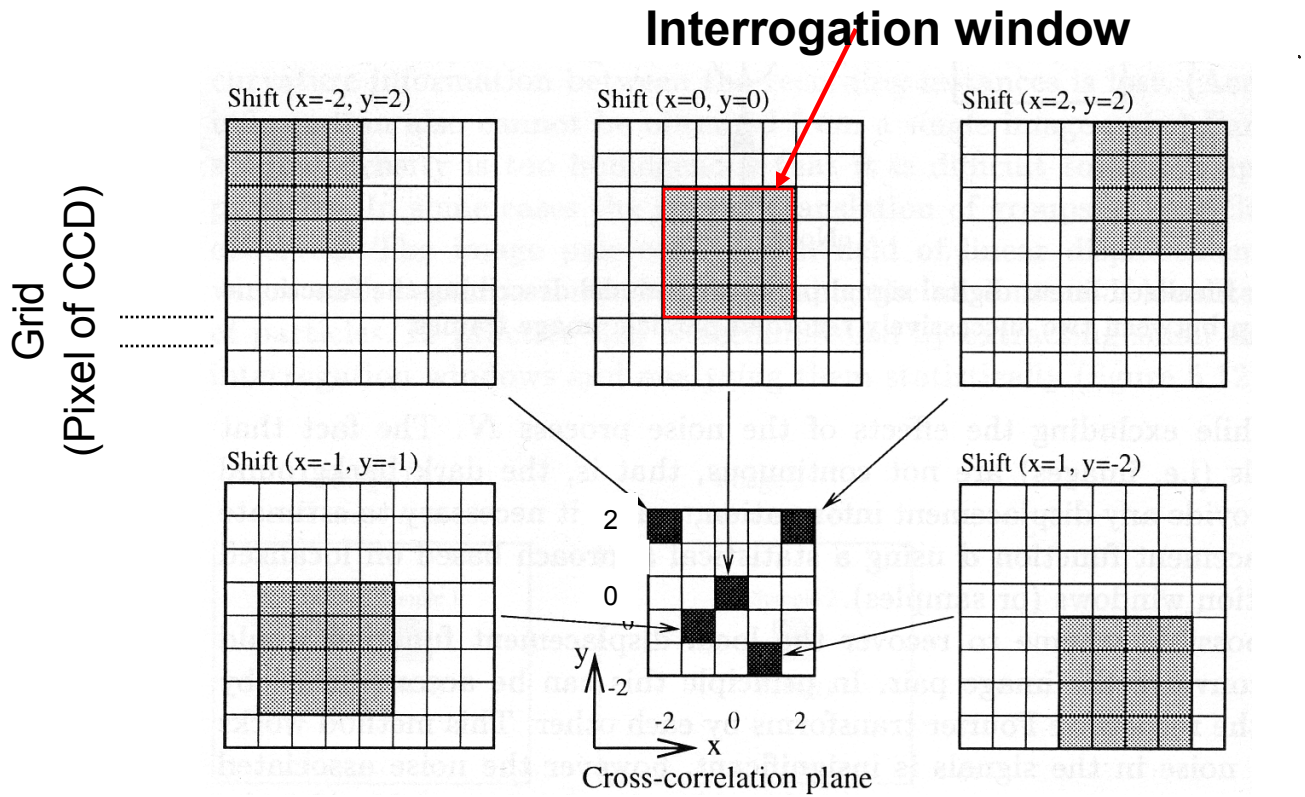
Interrogation windows,

they determine spatial resolution

Particle Image Velocimetry

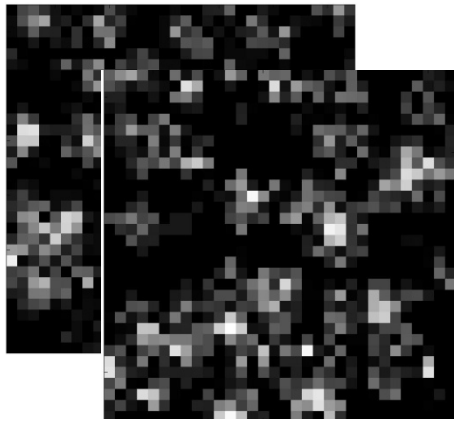
- **Cross-correlation**

$$R_{II'}(x,y) = \sum_{i=-K}^{K} \sum_{j=-L}^{L} I(i,j) I'(i+x, j+y)$$



Particle Image Velocimetry

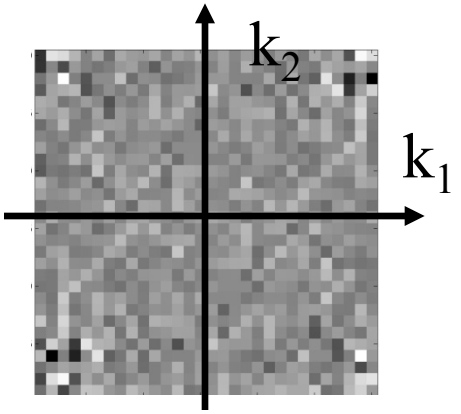
- **Practical realization**

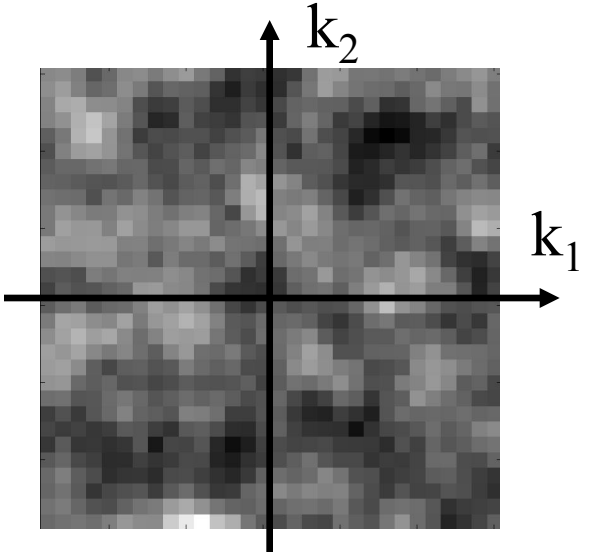


Interrogation volume size

Here: 32 x 32 pixel

FFT
(real to complex)

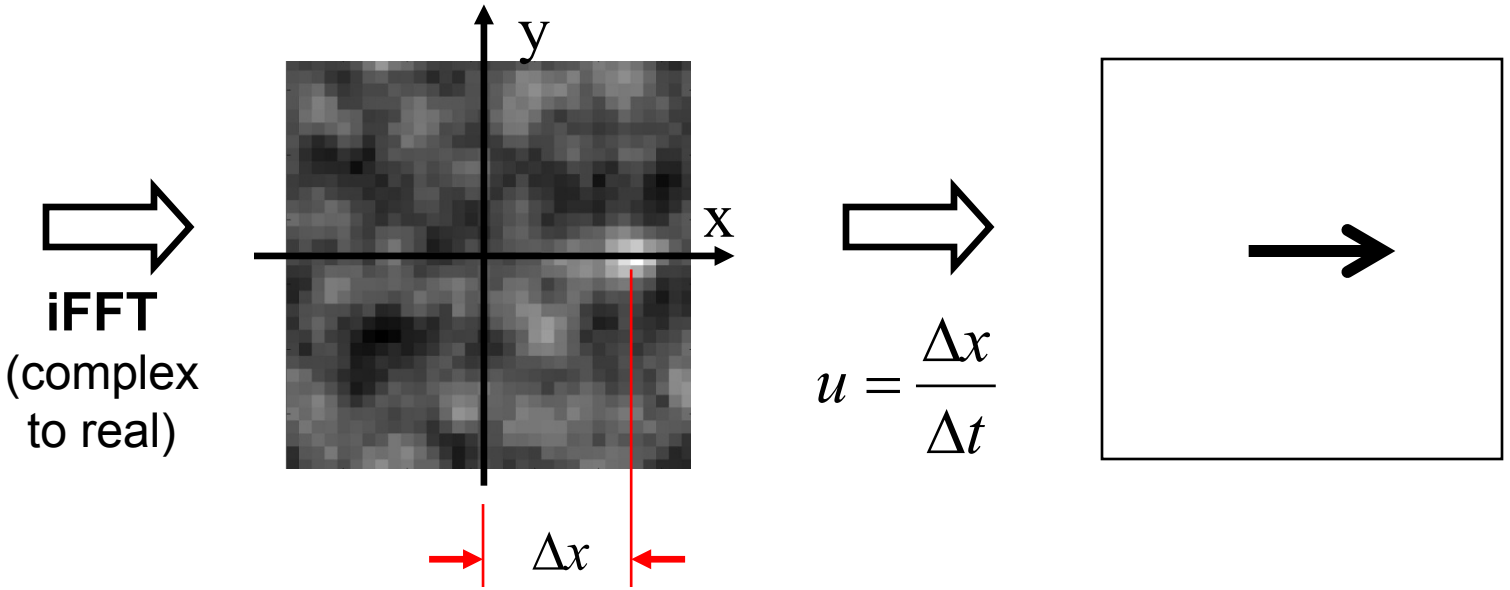




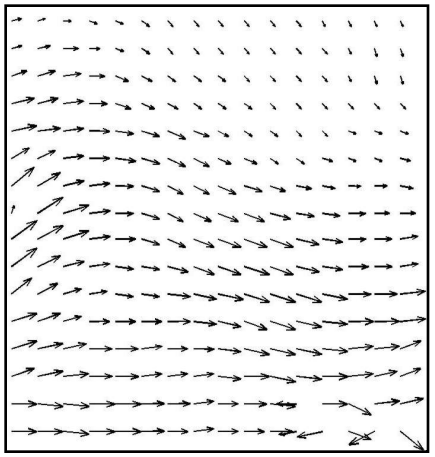
$$\hat{R}_{II}(i,j) = \hat{I}_1(i,j) \cdot \hat{I}_2(i,j)$$

Particle Image Velocimetry

- **Practical realization**



- **Result: instantaneous 2-component velocity field in a plane**



Particle Image Velocimetry

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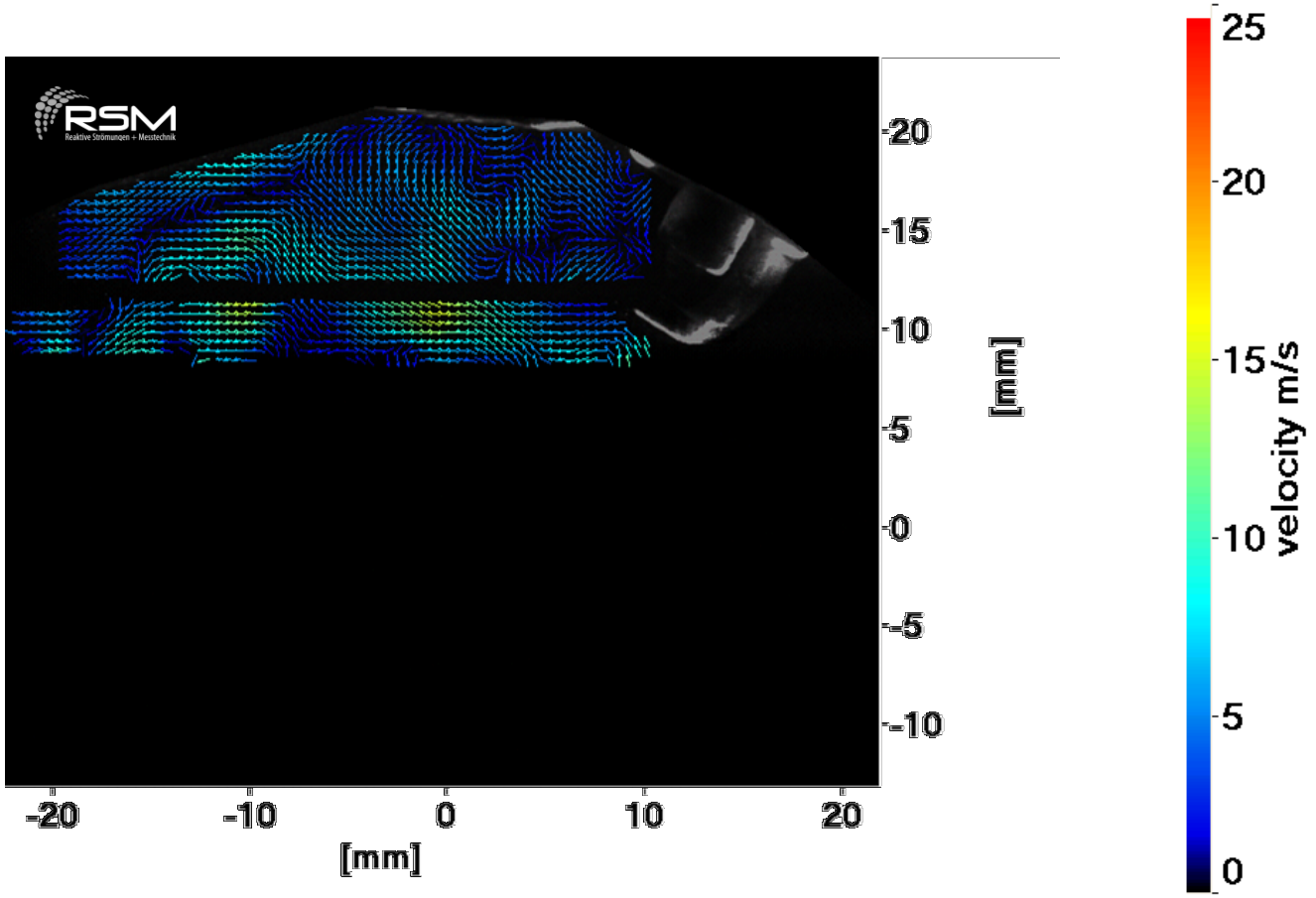
- **Example:**
  - PIV at 6 kHz repetition rate to study in-cylinder flow field

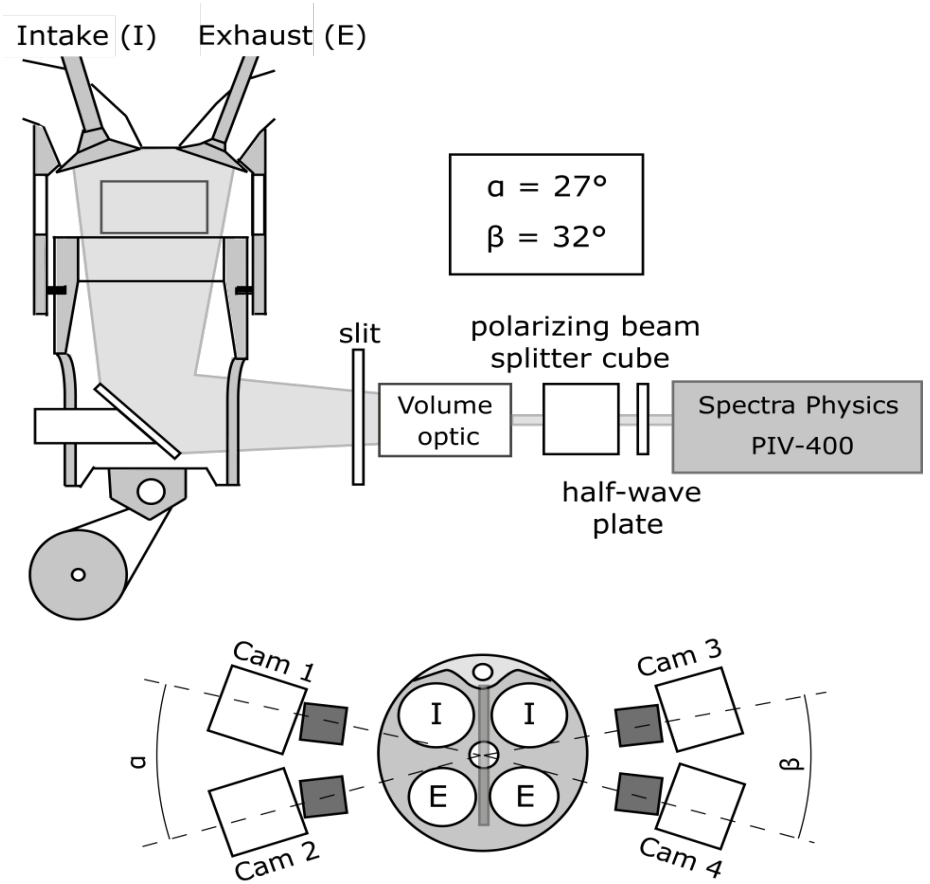


Particle Image Velocimetry

- **Measured variables**
  - Mean, variance and Reynolds stresses as in 2-component LDV
  - Instantaneous velocity gradients (w velocity in z-direction)
    - Out-of-plane vorticity $\omega = 1/2\left|\partial \mathrm{w}/\partial r - \partial \mathrm{v}/\partial z\right|$
    - 2D-Dilatation $\left(\nabla \cdot V\right)_{2D} = \left(\partial \mathrm{w}/\partial z + \partial \mathrm{v}/\partial r\right)$
  - Less suited for spatial correlation measurements

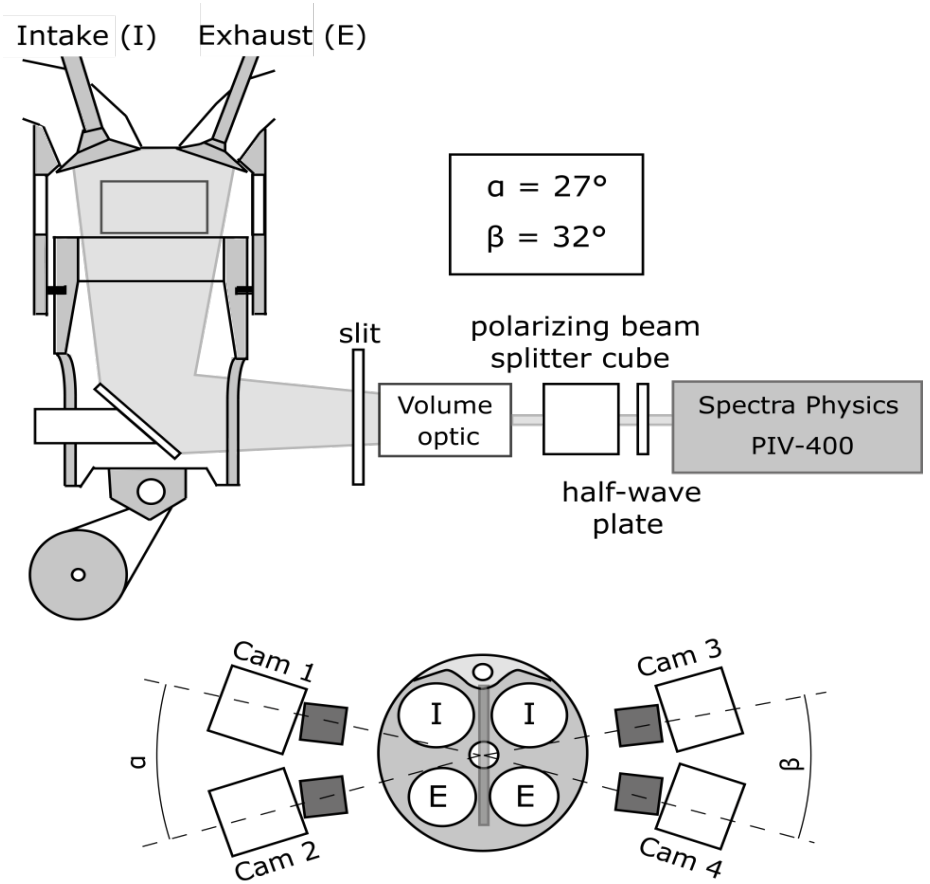
Extension to tomographic PIV: Illumination

- **Illumination**
  - Dual-cavity laser (PIV400, Spectra Physics)
  - Avg. 375 mJ per single pulse
  - Phase-locked acquisition during intake and compression (<5 Hz)
  - Volume of: 48 x 35 x 4/8 mm



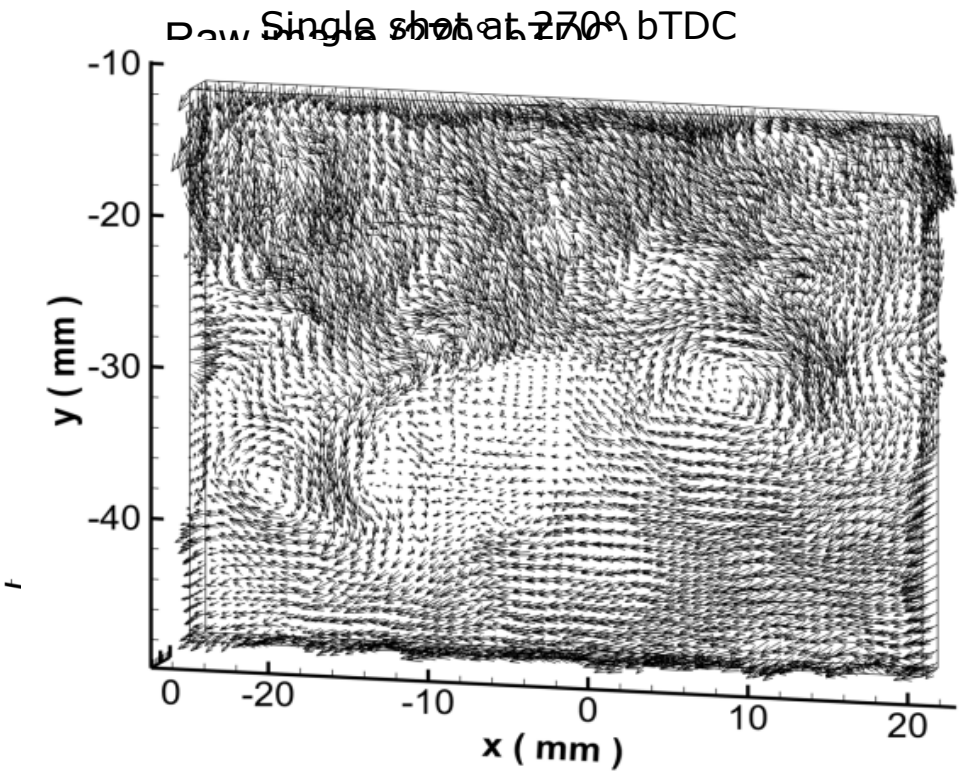
Extension to tomographic PIV: Detection

- **Detection**
  - Interline transfer CCD (ImagerIntense, LaVision, 1376x1040 pixels)
  - Nikon 50 mm, 1.4 (f# 16)
  - Limitation of Camera angles due to cylinder head bolts



Tomo PIV Processing

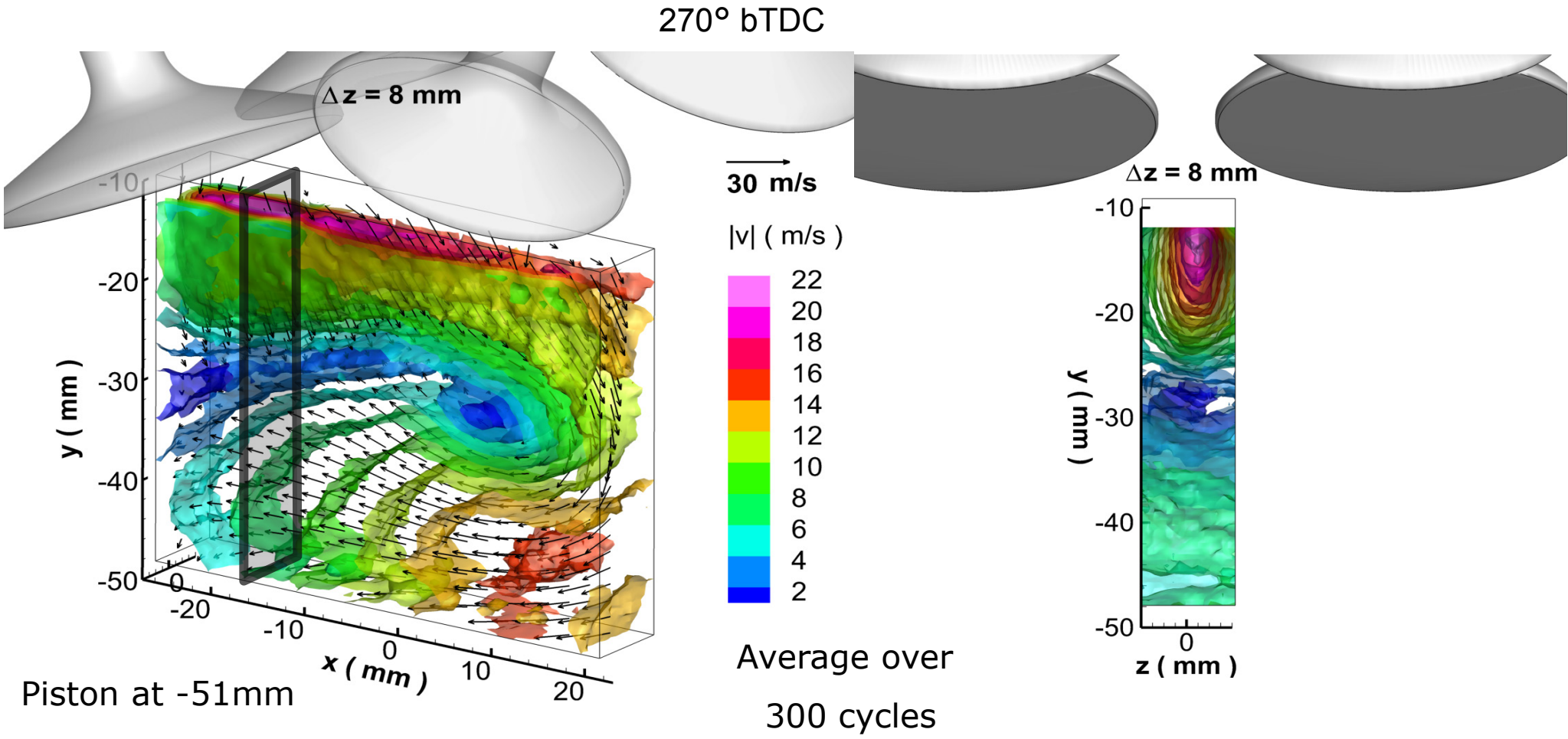
- **Tomo-PIV processing using DaVis 8.1**
- **Image pre-processing**
  - Subtract sliding average (3px)
  - Local intensity normalization
  - Gaussian smoothing
  - Sharpening filter
- **MART Reconstruction** (multiplicative algebraic reconstruction technique)
- **Volume correlation (Finale size)**
  - 4mm: 48x48x48 pixel (0.4mm/vector)
  - 8mm: 64x64x64 pixel (0.6mm/vector)
- **Post-processing**
  - Outlier detection (Neighborhood operation)
  - Gauss smoothing



0.04 - 0.05 ppp

Average Velocity Data – intake stroke

- **Iso-surface of average velocity magnitude during intake stroke**



Particle Image Velocimetry

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- **LDV versus PIV**
  - Seeding density
    - PIV: needs at least 10 particles per interrogation volume → for a fixed spatial resolution a minimal seeding density is required
    - LDV: seeding density can be as low as required (on the expense of data acquisition time), seeding density and spatial resolution are decoupled
  - Calibration/ data post processing
    - PIV: cross-correlation algorithm required, long CPU-times (→good statistics not common), “calibration” needed (pixel to millimeter)
    - LDV: fast online data processing by optimized CPUs, no calibration required
  - Measured variables
    - LDV: reliable “point-data”, investigation of local neighborhood by two-point LDV cumbersome
    - PIV: instantaneous velocity fields and gradients in different directions (spatial multi-point statistics accessible)

→ **LDV and PIV are complementary techniques**

Chapter 5:
Gas-Phase Thermometry

TU Darmstadt, Germany
Dept. of Mechanical Engineering
Institute for Reactive Flows and Diagnostics

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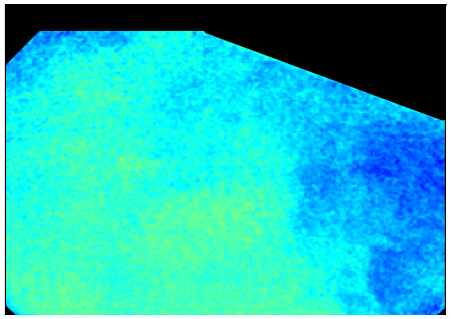
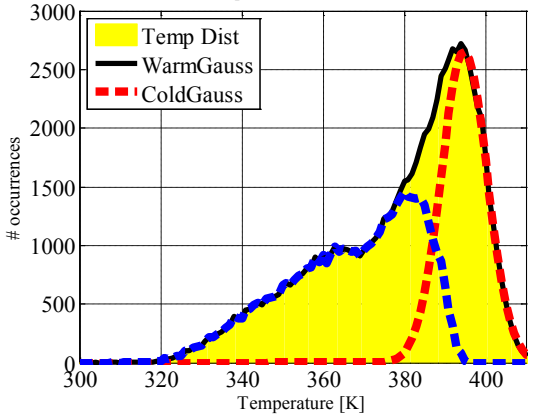
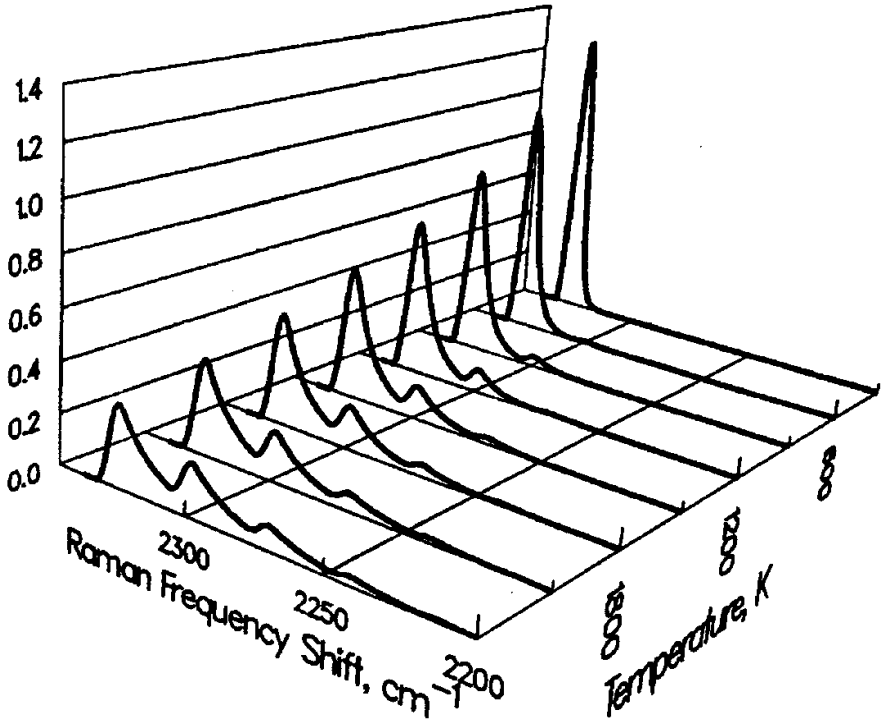
RSM Reaktive Strömungen + Messtechnik





A. Dreizler

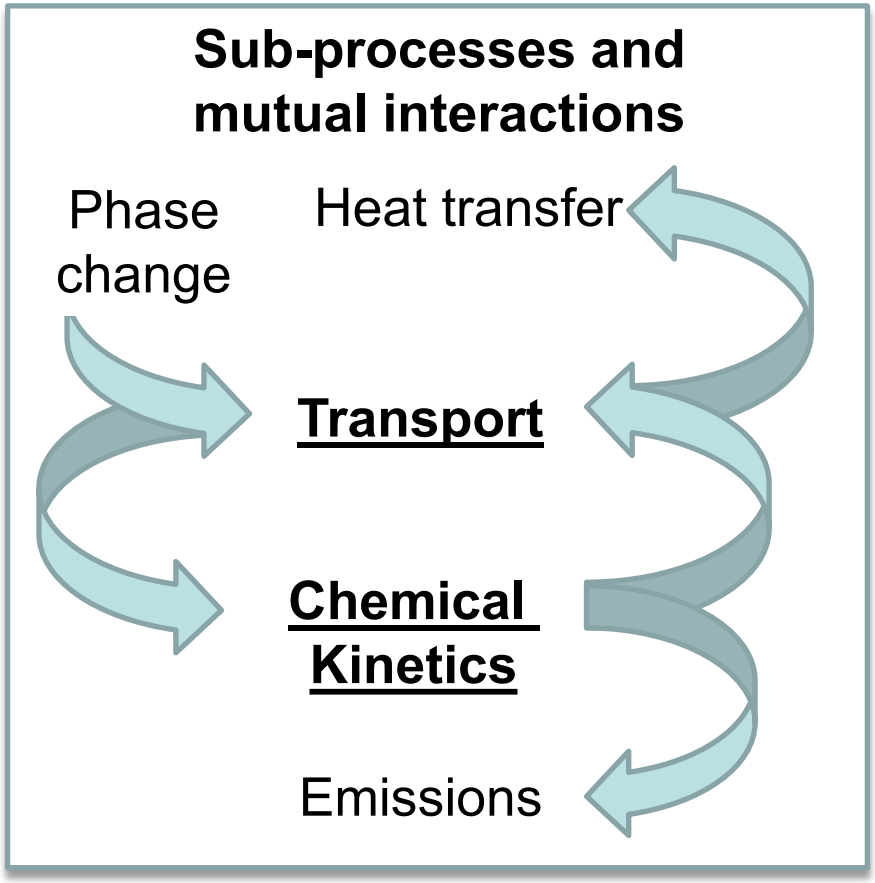
L. Boltzmann, 1844-1906
Source: Wikipedia



Source: Dr. A. Eckbreth

Combustion: coupled sub-processes

Combustion:
Energy conversion of chemically bound to thermal energy



→ Each of these sub-processes is significantly influenced by **local gas temperatures**

Need for accurate and precise temperature measurements to understand combustion

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- Temperature (gas) is key quantity with impact on
  - Chemical kinetics (Arrhenius-type reaction rates)
  - Gas density (equation of state)
  - Viscosity
  - Progress variable in premixed combustion

  → **Turbulence-chemistry interaction**
- Understanding combustion requires knowledge of local temperatures (gas)
  - Accurately: no systematic error (ideally)
  - Precisely: low statistical error (low noise, ..)
  - Locally: due to non-linear dependency of sub-processes on temperature

Laminar vs. turbulent combustion

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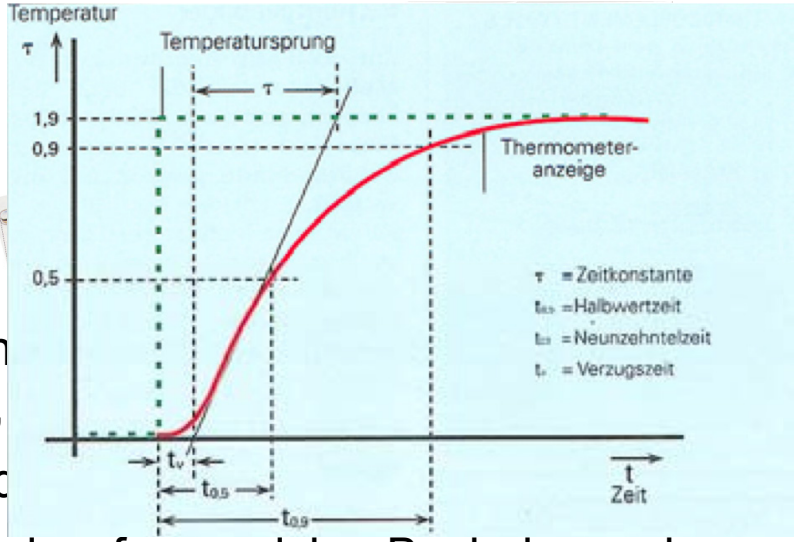
- **Laminar** and stationary combustion
  - No temporal variation
  - Large spatial variation (across heat release zone)

  → Resolution requirements
    - Time: none
    - Space: high, depends on pressure, fuel etc., method must alow for resolving smallest scales (ideally)
- **Turbulent** (statistically stationary) combustion
  - Large temporal variation
  - Large spatial variation (heat release zone, convection, mixt. preparation)

  → Resolution requirements
    - Time: resolve Bachelor time-scales (ideally)
    - Space: resolve Bachelor length-scales (ideally)

Intrusive vs. non-intrusive sensing (1)

- **Intrusive** sensors
  - Thermocouples
  - Resistance thermometer
  - Major disadvantages
    - Systematic errors (heat conduction
      flow, promoting catalytic reactions,
    - Not sustainable (melting point, oxic
    - Size: ~mm → spatial resolution too low for resolving Bachelor scales
    - Temporal response: first order system with large time-constants



→ **Not well suited for many applications in combustion research**

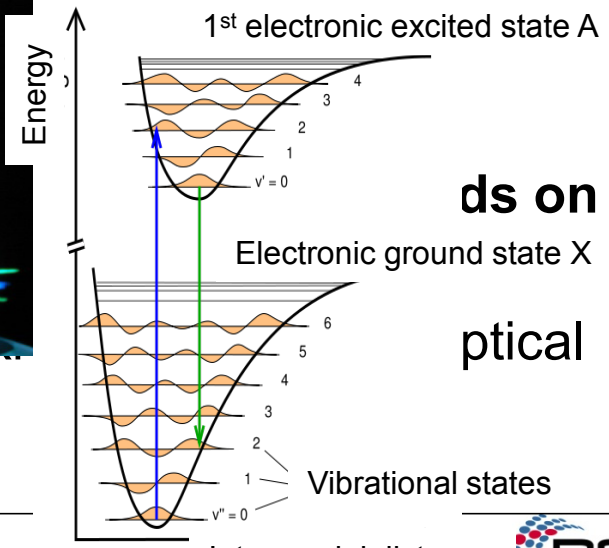
Intrusive vs. non-intrusive sensing (2)

- **Non-intrusive** sensors: based on spectroscopic methods
  - Thermal radiation: generally not applicable in gaseous flames, suitable for measuring particle temperatures if emissivity is known
  - Chemiluminescence (OH*, CH*,…): not in chemical equilibrium
  - Spectroscopic methods
    - Probing Boltzman states
    - Exploit temperatu r emission bands
    - Measuring densit

→ **Well suited fo**

→ **There is not t ds on purpose**

- **Disadvantag** ptical access



Spectroscopic methods – classification

- Based on
  - Boltzmann distribution

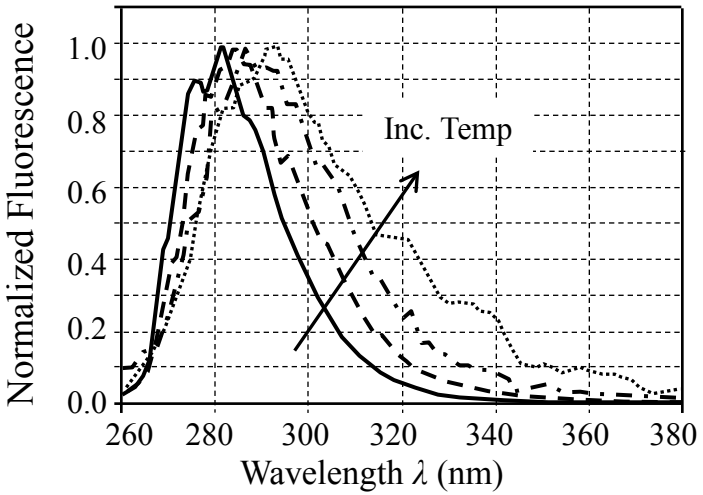
$$\frac{N_i}{N} = \frac{g_i \exp\left(-E_i / kT\right)}{\sum_j g_j \exp\left(-E_j / kT\right)} = \text{unique function of } T$$

g_i: degeneracy factor E_i: energy quantum state; both from quantum mechanics

$\sum$... : partition function

  - Temperature-dependent absorption/emission
  - Density *(N/V)* measurements

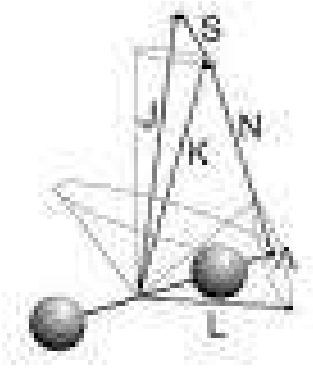
$$pV = NkT \rightarrow T = \frac{pV}{Nk}$$



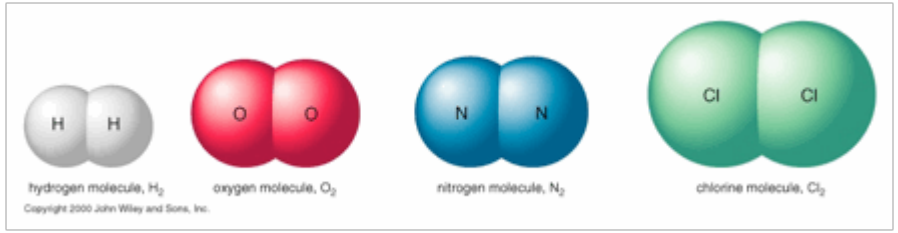
Restriction to diatomic molecules

- Two atoms, covalent bounded
- Degrees of freedom
  - 3 translation
  - Electronic (here only valence electron considered)
  - 1 vibrational
  - 2 rotational (degenerated)
- In combustion degrees of freedom not necessarily in equilibrium!

→ Translational, electronic, vibrational, and rotational temperatures not always identical

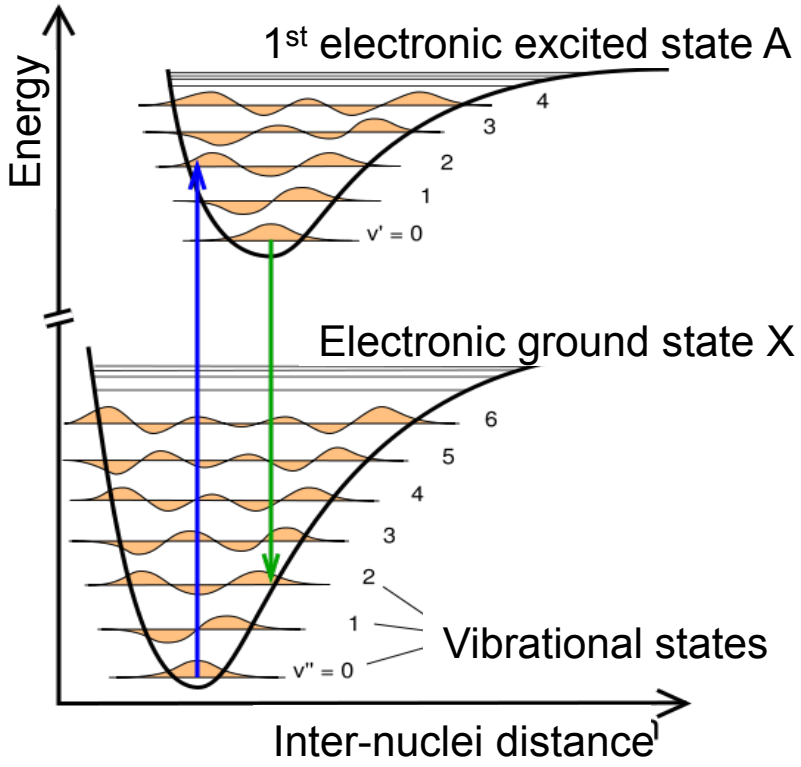


Source: Wikipedia



Source: Wiley and Sons

Internal energies of diatomic molecule



Rotational sub-levels not shown

$$T = T^{el} + S(\mathrm{v}, J) = T^{el} + G(\mathrm{v}) + F(\mathrm{v}, J)$$

$$= T^{el} + \omega_e\left(\mathrm{v}+\frac{1}{2}\right) - \omega_e x_e\left(\mathrm{v}+\frac{1}{2}\right)^2 + \omega_e y_e\left(\mathrm{v}+\frac{1}{2}\right)^3 + \ldots + B_{\mathrm{v}} J(J+1) - D_{\mathrm{v}} J^2 (J+1)^2 + \ldots.$$

Temperature measurement via Boltzmann (1)

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- Boltzmann distribution (diatomic molecule)
  - **Rotational** sub-levels

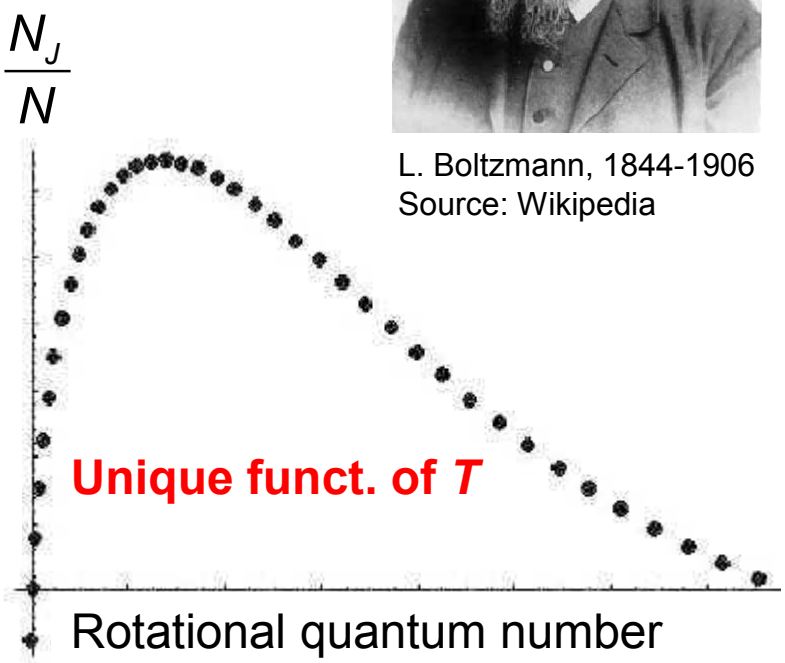
$$\frac{N_J}{N} = \frac{(2J+1)\exp(-E_J / kT)}{\sum_J (2J+1)\exp(-E_J / kT)}$$

with J rotational quantum number

(fractional population)

  - Already at T = 300 K many rotational sub-levels populated because energy separation between adjacent small (10 – 100 cm^{-1})

L. Boltzmann, 1844-1906
Source: Wikipedia



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Temperature measurement via Boltzmann (2)

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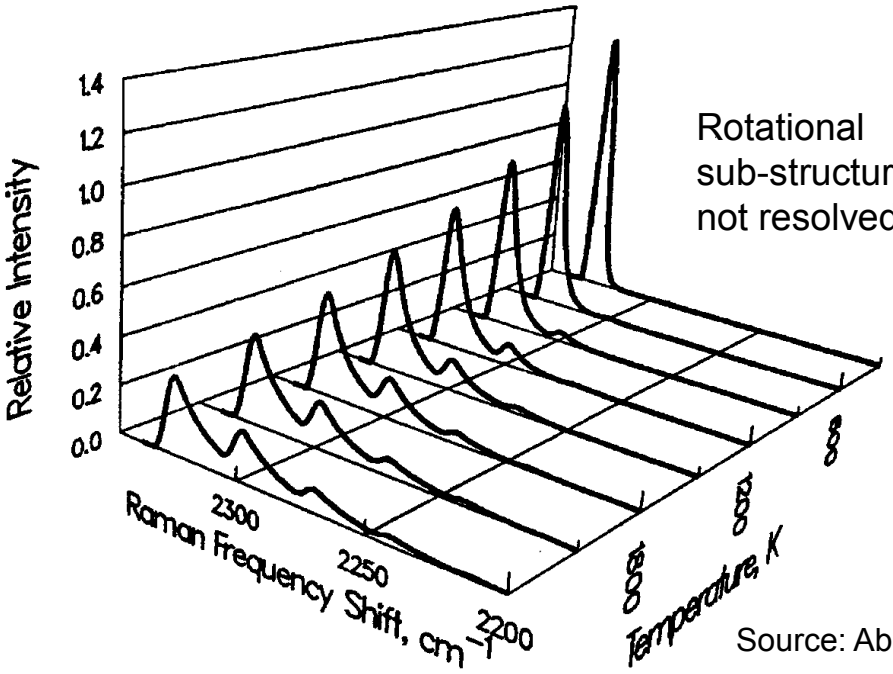
- Boltzmann distribution (diatomic molecule)
  - **Vibrational** sub-levels

$$\frac{N_v}{N} = \frac{\exp\left(-E_v / kT\right)}{\sum_v \exp\left(-E_v / kT\right)}$$ with v vibrational quantum number

  - Vibrationally excited levels n

Example N_2:

- Energy gap between v''=0 and v'=1 ~2300 cm^{-1}



Rotational sub-structure not resolved

Source: Abacus

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Temperature measurement via Boltzmann (3)

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- Boltzmann distribution (diatomic molecule)
  - **Electronic** sub-levels

$$\frac{N_{ES}}{N} = \frac{\exp\left(-E_{ES} / kT\right)}{\sum_{ES} \exp\left(-E_{ES} / kT\right)}$$ with *ES* quantum number of electronic state

  - Energy separation > 10000 cm^{-1}

→ In general: Not significantly populated at combustion temperatures

Exception: Atomic tracer such as indium (not considered in detail during this lecture)

→Measure temperature via the distribution of rotational quantum states

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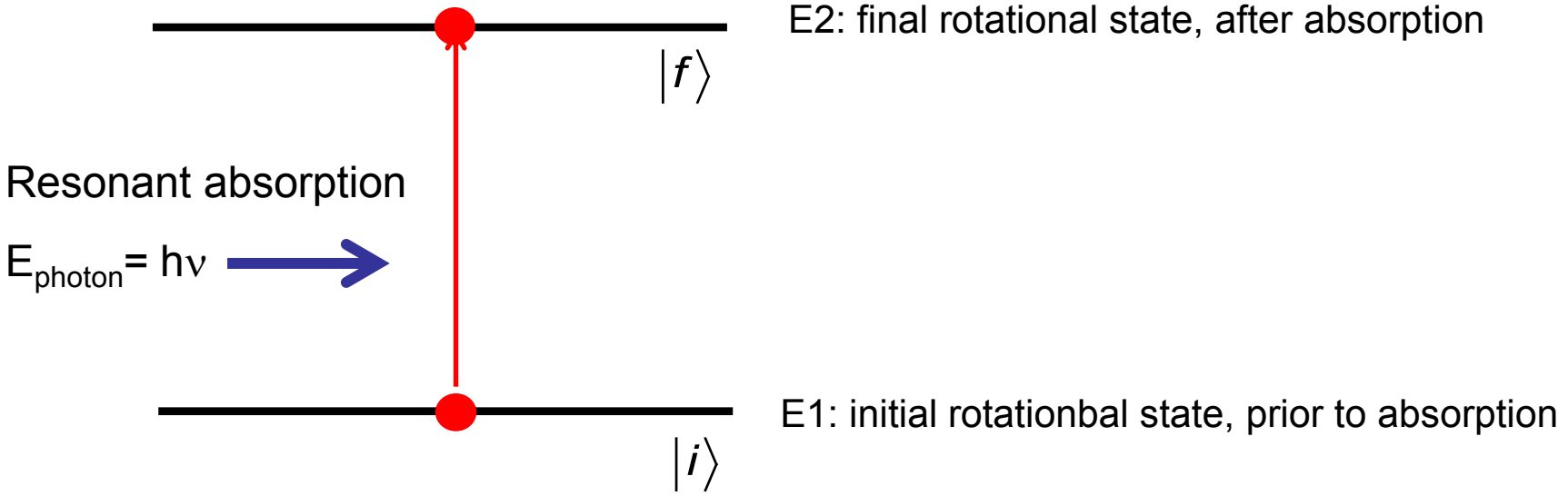
Rotational temperatures – by microwaves

- **Task**: measuring Boltzmann distribution of rotational sub-levels
  - **Single photon** resonant processes
  - Pure rotational spectroscopy

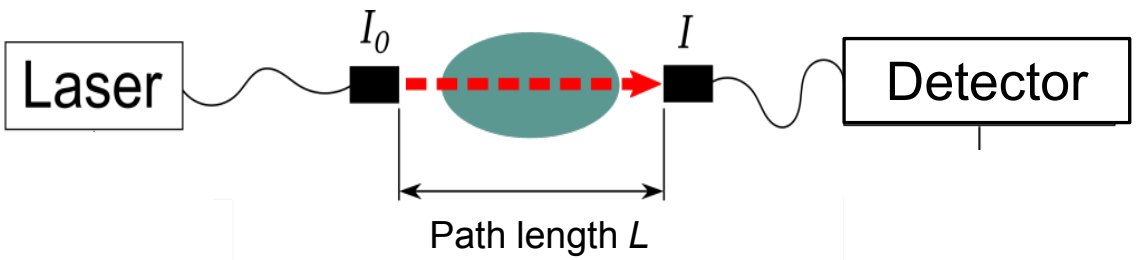


  - Energy separation: 10 – 100 cm^{-1} → **microwave radiation**

→ **Not common** in combustion (low spatial res., background radiation)

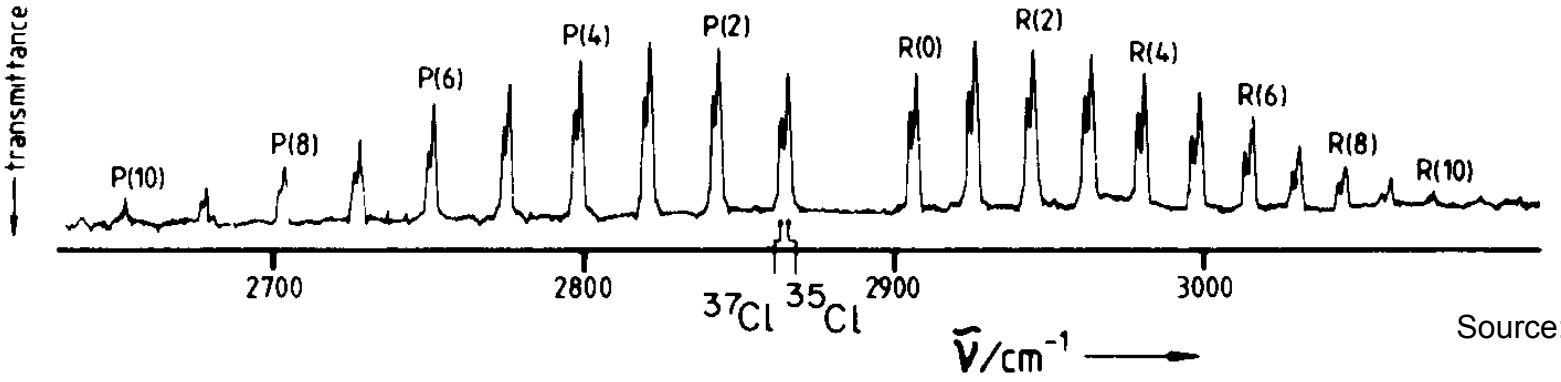
Rotational temperatures – by IR spectroscopy

- **Rotational-vibrational spectroscopy**
  - Energy separation: ~1000 – 4160 cm^{-1} → infrared radiation
  - Example HCl absorption spectrum



$$N_J = \frac{\ln\left(I\,(x=L)\,/\,I_0\right)}{x \cdot \sigma_{j \leftarrow i}}$$

Discussion of spectrum: see following slides

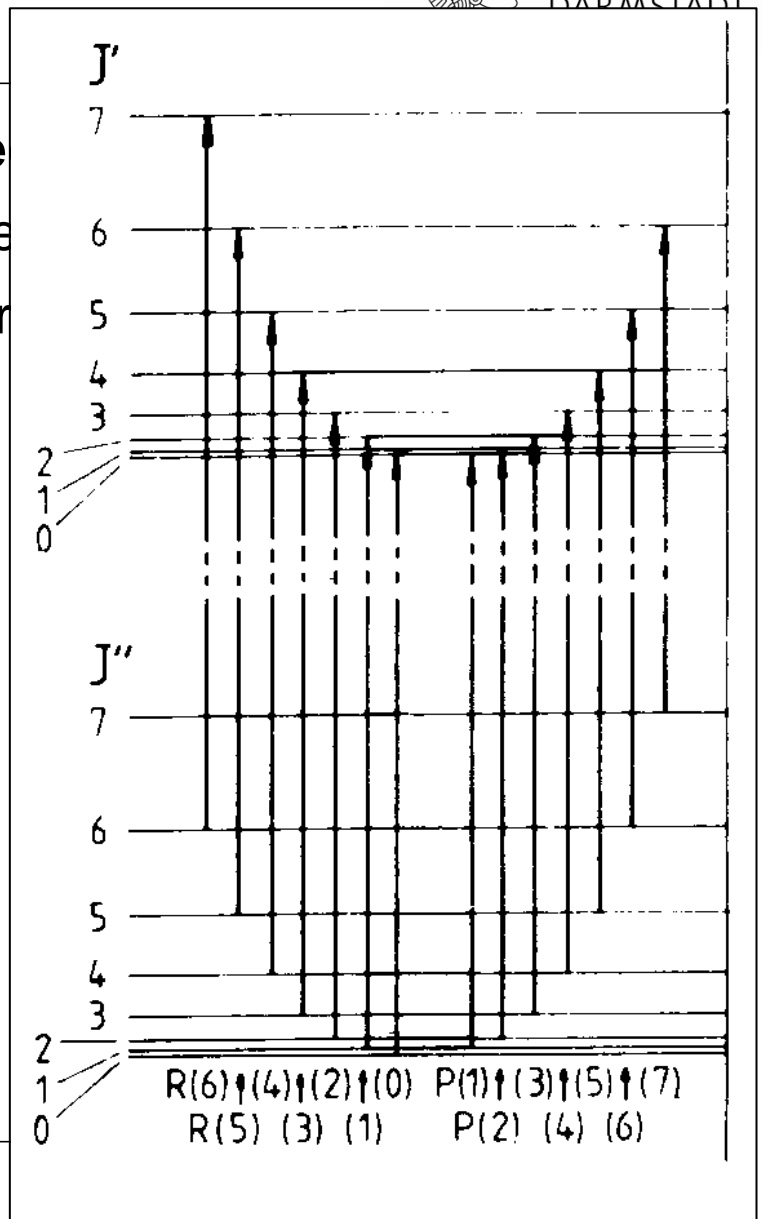


Source: Hollas

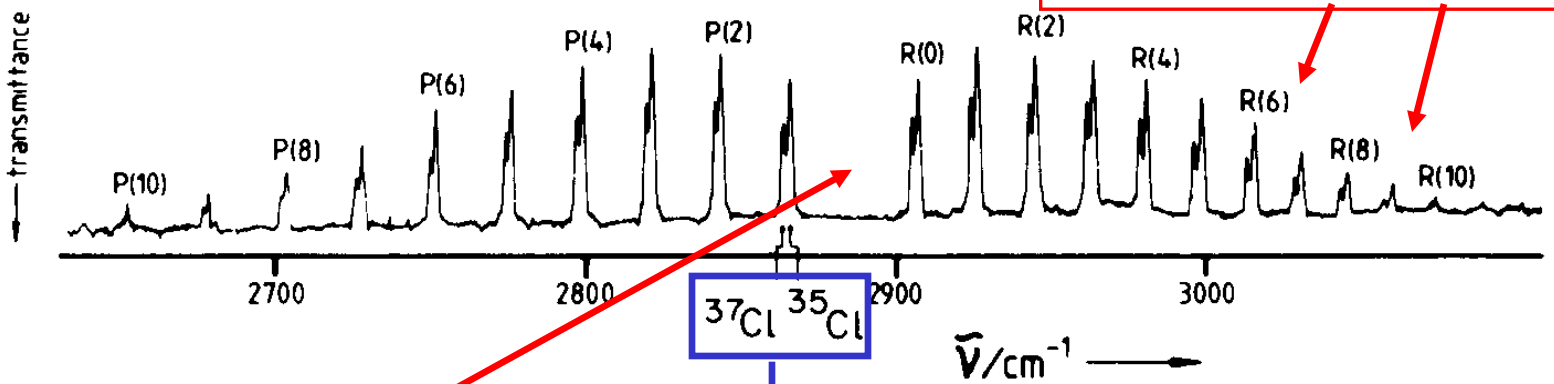
Selection rules

- **Fundamental finding from quantum me**
  - Change of vibrational quantum numbe
  - Change of rotational quantum number
  - But exceptions (for example NO)
  - Notation

$$\Delta J = 0 \Rightarrow \text{ Q-lines}$$
$$\Delta J = 1 \Rightarrow \text{ R-lines}$$
$$\Delta J = -1 \Rightarrow \text{ P-lines}$$



Spectrum interpretation HCl



$$v' = 1 \leftarrow v'' = 0$$

Final vib state

Initial vib state

Temperature from Boltzmann distribution

Line intensities J-dependent

Zero gap: no Q-line

Wave number: units in spectroscopy

2 isotopes → Separated due to different inertias $I=mr^2$

Rotational temperatures by UV/VIS spectroscopy (1)

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- **Electronic spectroscopy**: change of electronic, vibrational and rotational states due to absorption of UV or VIS photon
  - Energy separation > 10000 cm^{-1}
  - Selection rules (extract only)

$\Delta J = 0, \pm 1$ → Q-, R-, P- lines

$\Delta v = 0, \pm 1, \pm 2, \ldots$ → Compare „Franck-Condon principle“

→ For Hund case (a) (most important rules)

$\Delta\Lambda = 0, \pm 1$ $\Sigma-\Sigma$, $\Pi-\Sigma$ or $\Delta-\Pi$ transitions. Not allowed for example $\Delta-\Sigma$ transitions

$\Delta S = 0$ Allowed: Triplett – Triplett or Singulett – Singulett transitions
Spin forbidden: Singulett – Triplett transitions

Λ:Projection of orbital momentum *L* on molecule axis
S: Multiplicity

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Rotational temperatures by UV/VIS spectroscopy (2)

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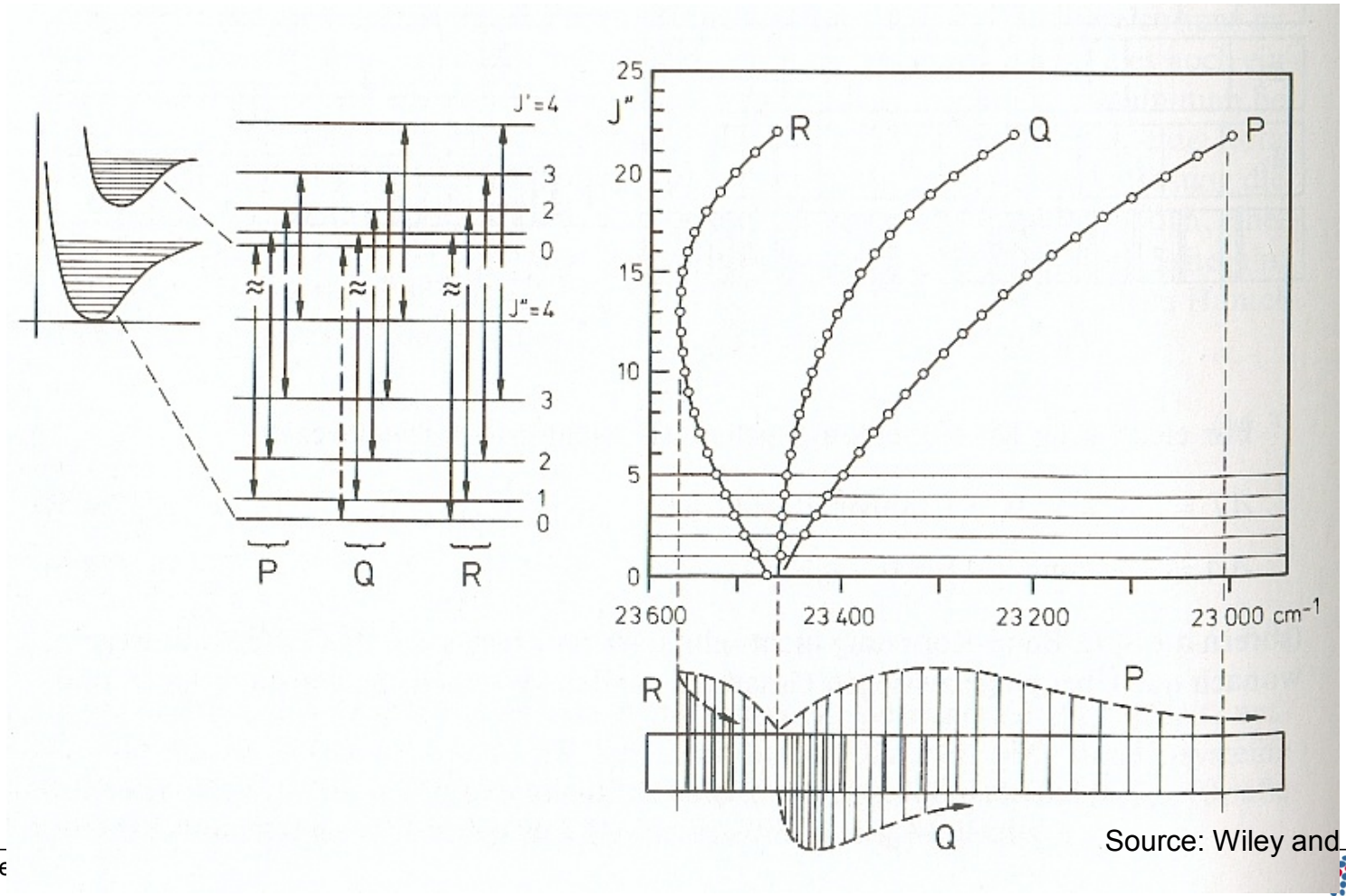
- **Electronic spectroscopy**:



Source: Wiley and Sons

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Rotational temperatures by UV/VIS spectroscopy (3)

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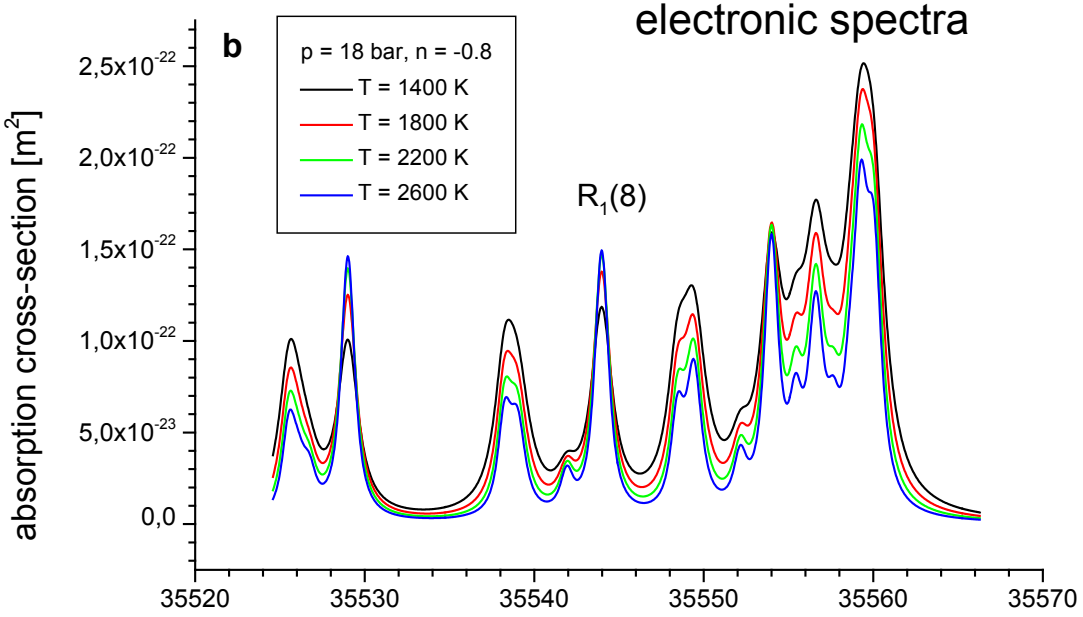
- OH $A^2\Sigma \leftarrow X^2\Pi$ (v´=1 ← v´´=0)–transition
- R-branch, band head

Temperature dependent electronic spectra



Methods in the IR & UV/VIS for temperature measurements via Boltzmann distribution

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- Laser absorption spectroscopy (LAS)
- Laser-induced fluorescence (LIF)
- Raman spectroscopy (RS)
- Coherent anti-Stokes Raman spectroscopy (CARS)

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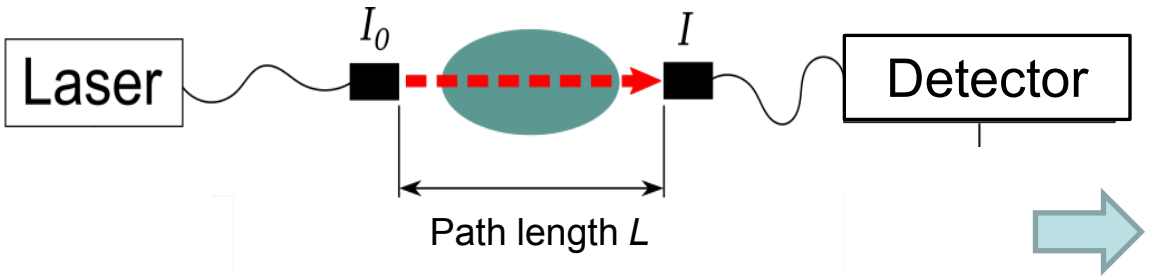
Laser absorption spectroscopy (1)

- Experimental setup



- Deduce number densities from Beer-Lambert's law

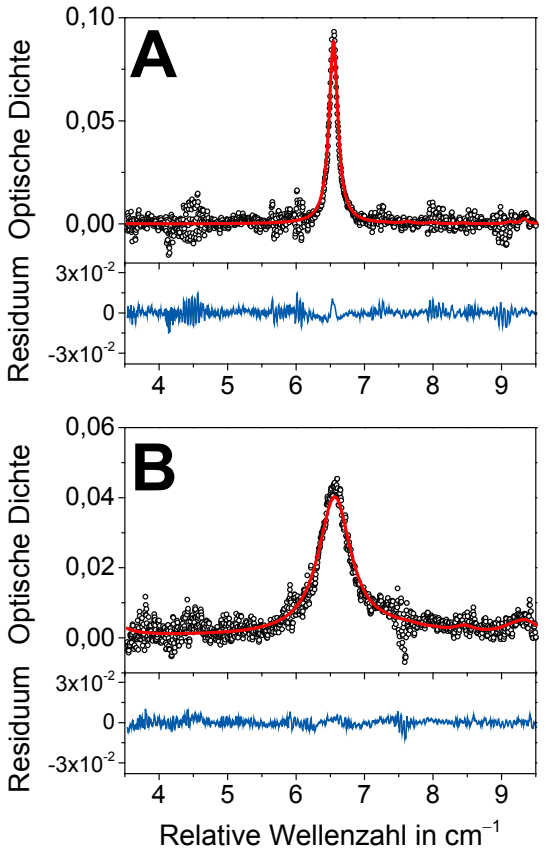
$$I(x=L) = I_0 \exp\left(-x \cdot N_J \cdot \sigma_{j \leftarrow i}\right) \Leftrightarrow N_J = \frac{\ln\left(I(x=L)/I_0\right)}{x \cdot \sigma_{j \leftarrow i}}$$

Laser absorption spectroscopy (2)

- Deduce temperature from Boltzmann distribution
  - Two-line thermometry

$$T = \frac{E_{J_2} - E_{J_1}}{k \ln\left(\frac{N_1(2J_2+1)}{N_2(2J_1+1)}\right)}$$

  - Multi-line thermometry: by spectral fit



Laser absorption spectroscopy (3)

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- Advantages
  - Sensitive
  - Accurate (no calibration required if spectroscopic details such as term values, line strengths, line broadening mechanisms known)
  - High accuracy, needs multi-line thermometry (for instantaneous T-measurements these requires rapid tuning of laser frequency and fast detection)
  - High spatial resolution perpendicularly to laser path
- Disadvantages
  - Line-of-sight (LOS): no spatial resolution along laser path, needs homogeneous distribution along laser path
  - Multi-line thermometry needs fast tuning of laser and fast detector

→ **Great in laminar flames, not easily applicable in turbulent flames (LOS)**

Laser Induced fluorescence (1)

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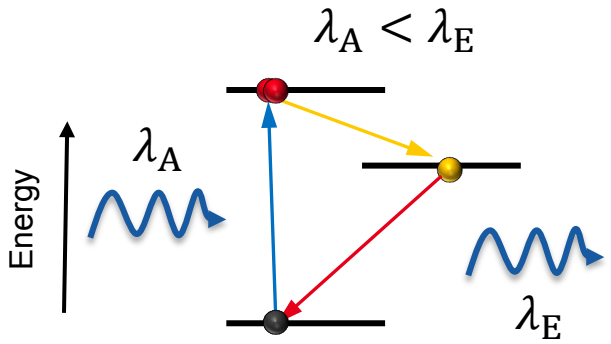
Step 1: Absorption

- Electronic excitation of molecules by laser radiation
- Wavelength λ_A



Step 2: Spontaneous emission (fluorescence)

- Spectrally red-shifted $\lambda_A < \lambda_E$
- Upper state lifetime typically few ns for flame conditions
- Measure of local number density

- Linear LIF regime

$$I_{LIF}(x) = N_1(x)\sigma(\nu)I_{laser}(x)\frac{\tau_{tot}}{\tau_{sp}}U\frac{\Omega}{4\pi}\varepsilon\eta$$

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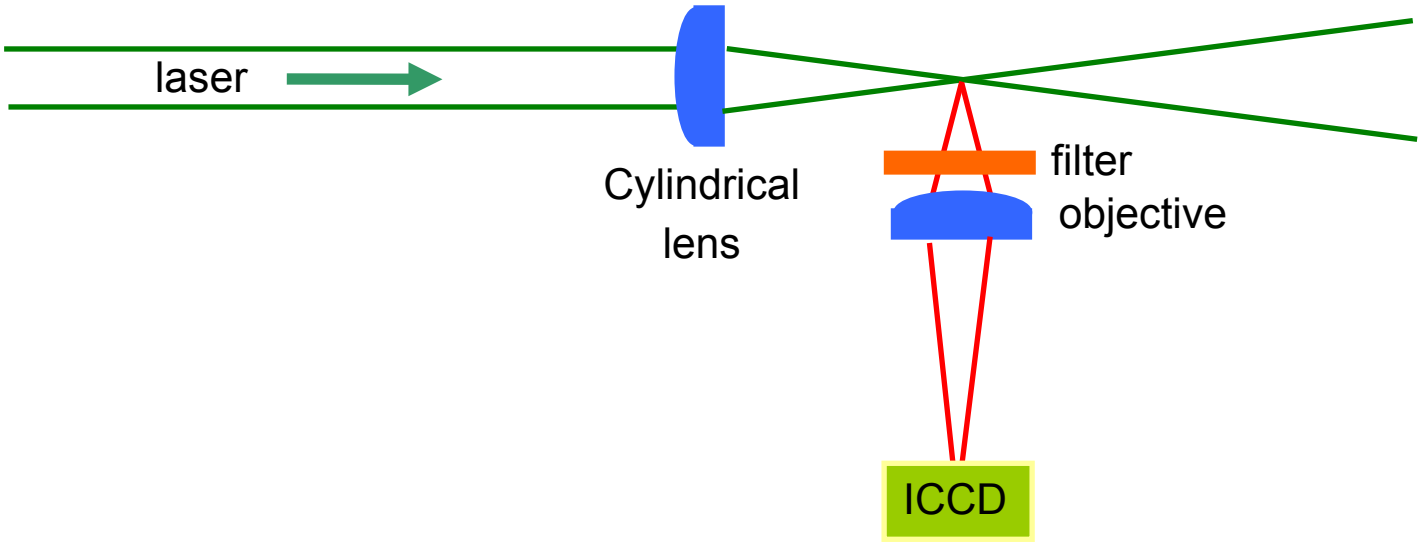
Laser Induced fluorescence (2)

- Experimental setup



Laser Induced fluorescence (3)

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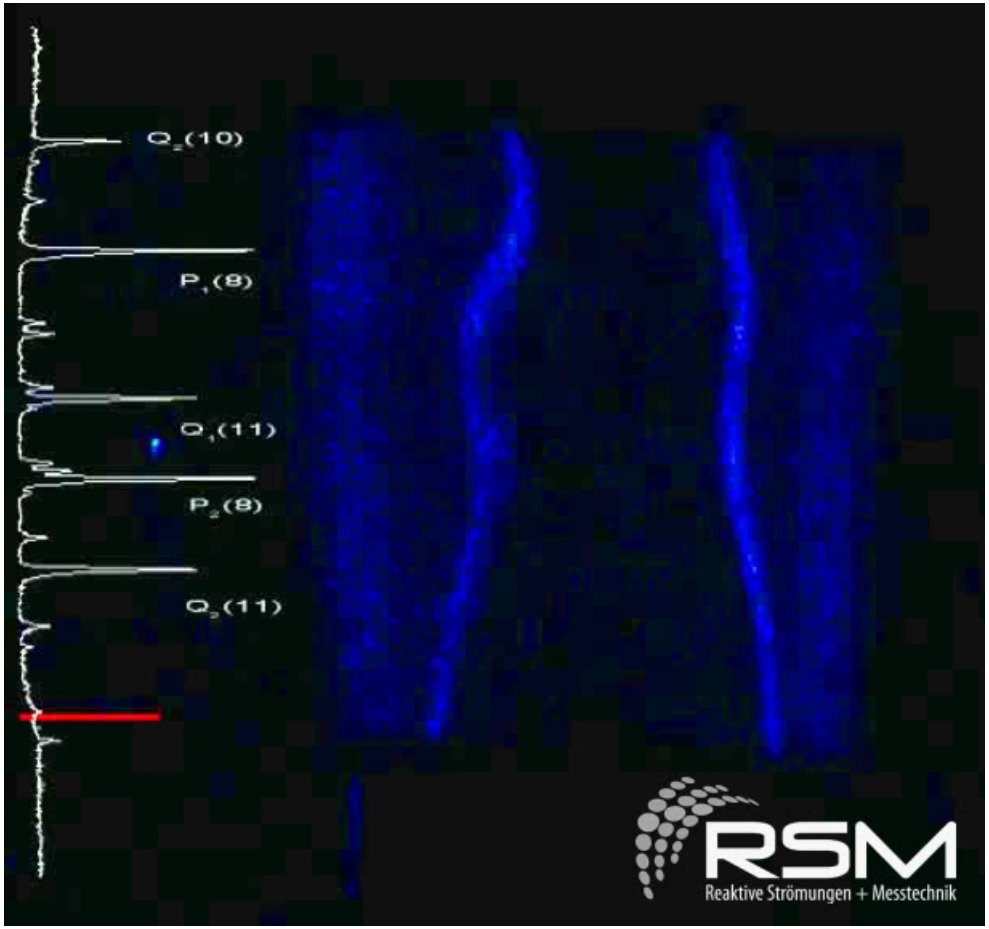
- Flame front visualization in CH_4/air Bunsen flame, p = 1 bar
- Excitation by tunable KrF excimer laser at ~248 nm



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Laser Induced fluorescence (4)

- **Two-line** thermometry:
  - excite two different transitions
  - Transitions selected such that ratio of number densities N_1 and N_2 vary sensitively with temperature
  - But: number density should not be too low for reasonable signal-to-noise ratio
- Calculate ratio of two LIF Signals $I_{LIF,i}(x) = N_i(x) U \sigma I_{laser,i}(x) \gamma_i(\nu) \frac{\tau_{tot}}{\tau_{sp}} \frac{\Omega}{4\pi} \varepsilon \eta$

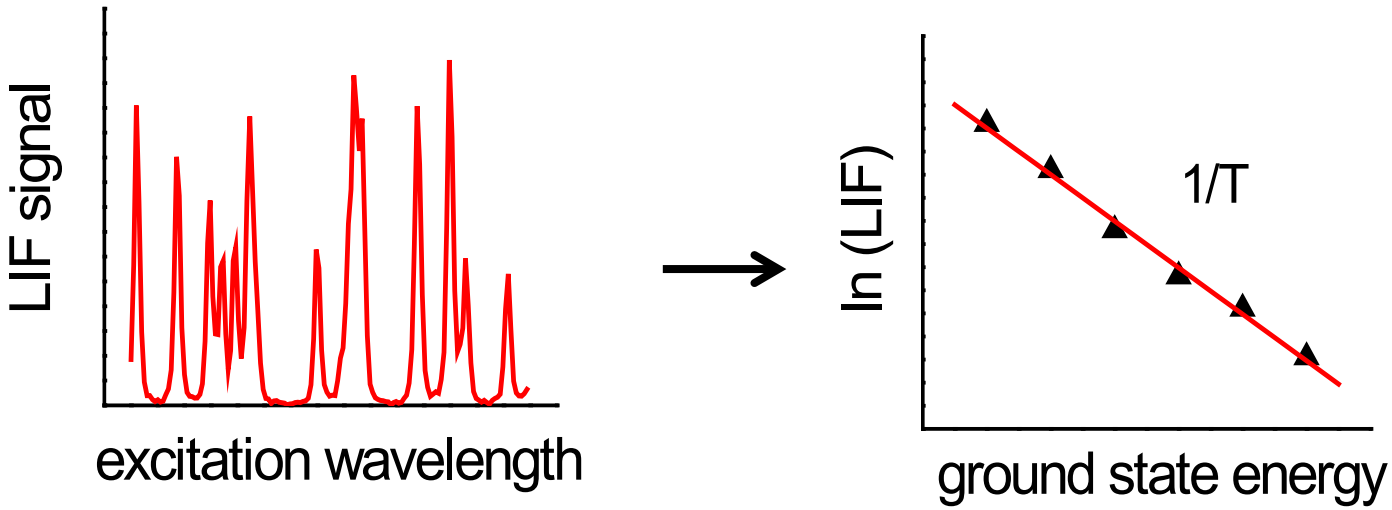
→ Yield **ratio**

$$R_{12} = \frac{I_{LIF,1}}{I_{LIF,2}} = \frac{c_1 \; I_{laser,1} \; g_1 \exp(-E_1 / kT) \; B_1 \; \gamma_1(p,T) \; \tau_{eff,1} / \tau_{sp,1}}{c_2 \; I_{laser,2} \; g_2 \exp(-E_2 / kT) \; B_2 \; \gamma_2(p,T) \; \tau_{eff,2} / \tau_{sp,2}}$$

→ **Issue two-line thermometry: Low precision due to experimental noise**

Laser Induced fluorescence (5)

- **Multi-line thermometry**: measure entire excitation-fluorescence spectrum
- Method 1: Spectral fit of entire spectrum by variation of temperature
- Method 2: Plot ln(I_{LIF}) vs ground state energy and deduce temperature from slope



→ **Great in laminar flames, not applicable in turbulent flames as wavelength scan takes too long**

Laser Induced fluorescence (6)

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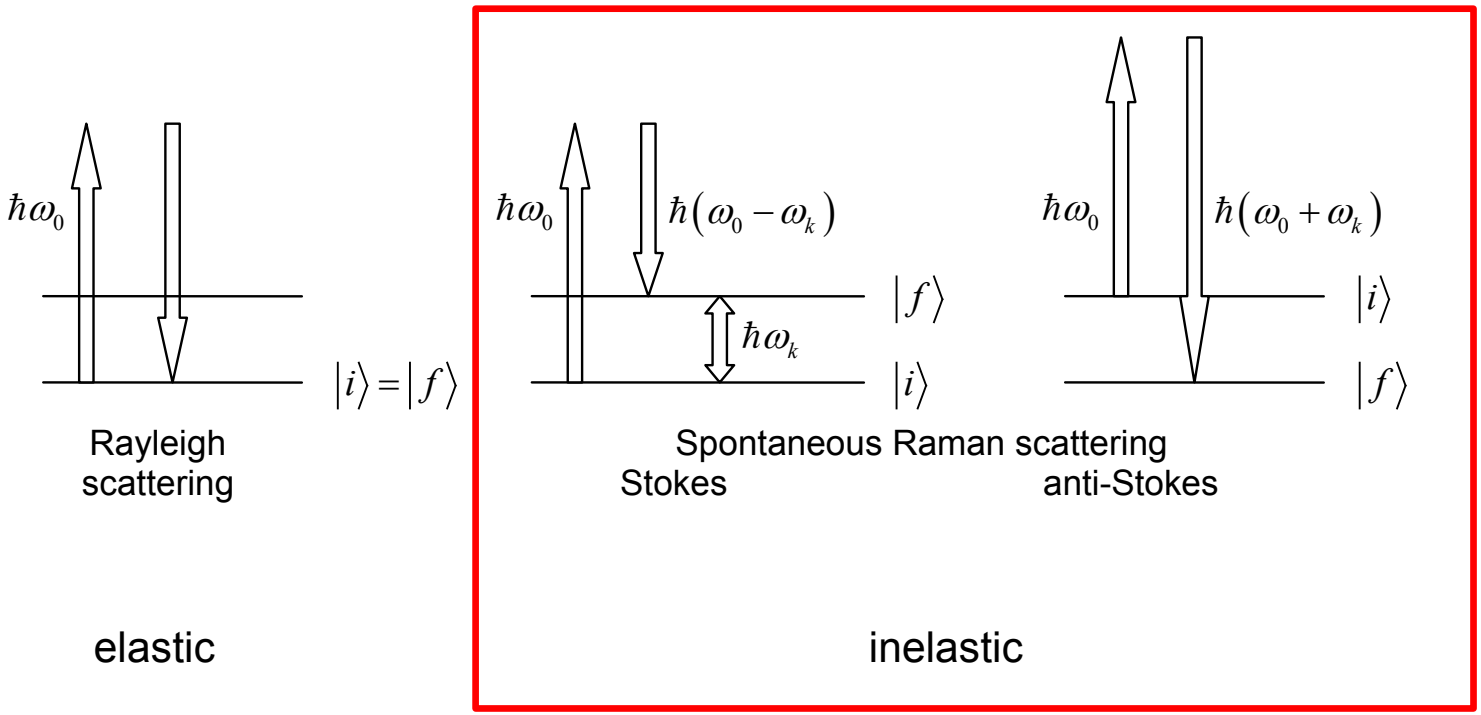
- **Choice of species** for LIF thermometry based on Boltzmann distribution
  - Naturally occurring molecules: OH radical, concentration level in typical flames sufficiently high only for T > 1500 K
  - Seeded species:
    - NO, chemically more or less inert, but may not be a good choice for cases studying auto-ignition (NO promotes auto-ignition), caution: NO is toxic
    - Indium, typically via InCl, for example dissolved in liquid fuel such as iso-octane, seeding is difficult in general (compare papers from Hult et al. or Nathan et al.)

Raman spectroscopy (1)

- Elastic and inelastic light scattering of photons off molecules



Raman spectroscopy (2)

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- Selection rules

$\Delta J = 0, \pm 2$

$\Delta J = 0 \rightarrow$ Q-branch

$\Delta J = +2 \rightarrow$ O-branch

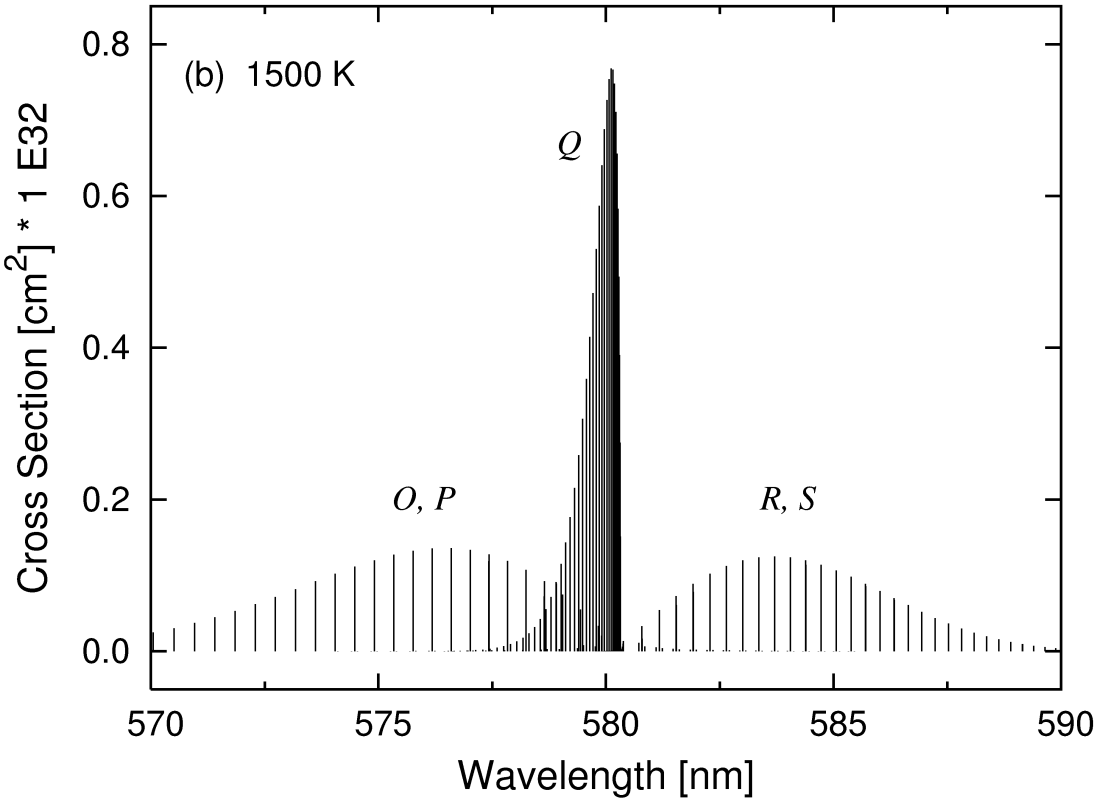
$\Delta J = -2 \rightarrow S$-branch

Oxygen molecule O_2, T = 1500 K

Simulated “stick spectrum” – infinite resolution

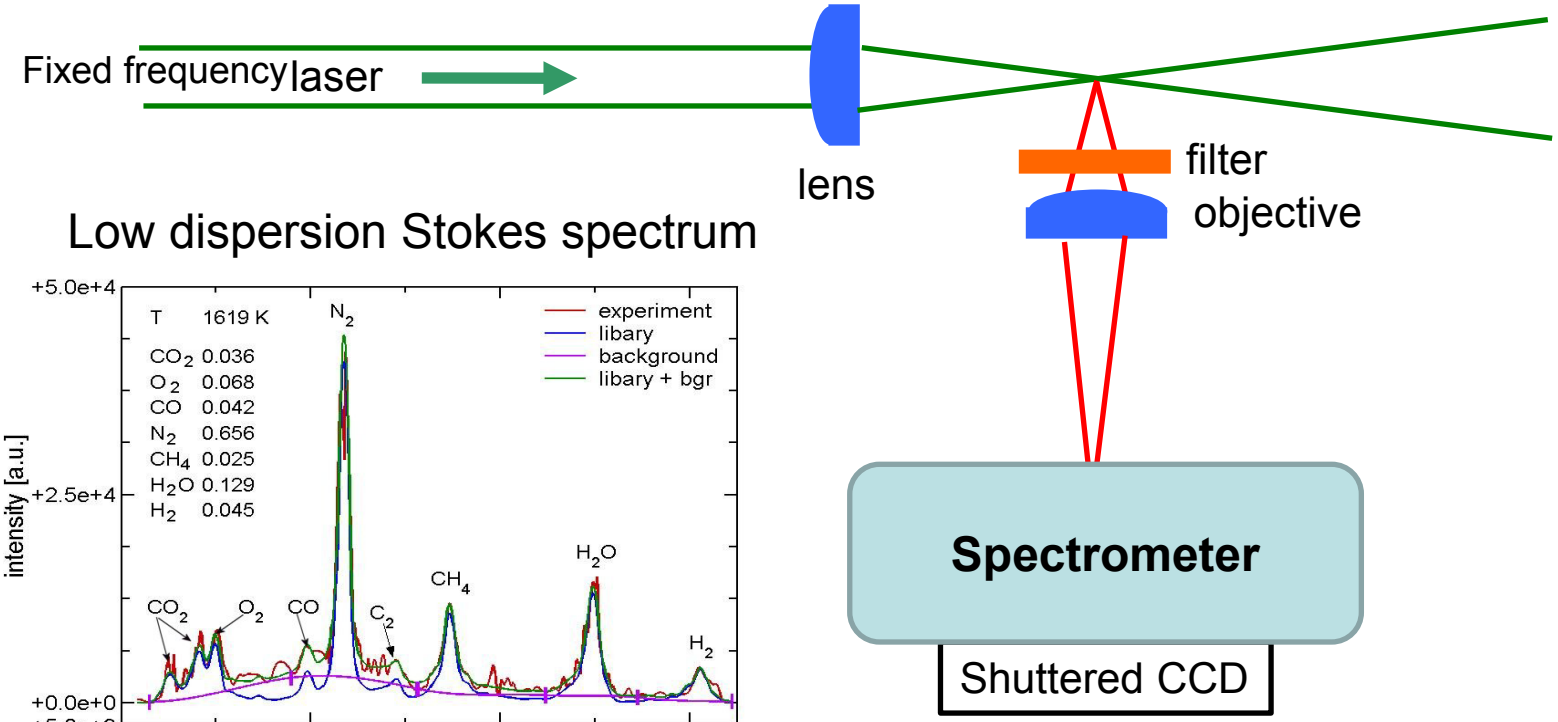
Ro-vibronic **Stokes-Raman**

Exception: very weak R and P-lines

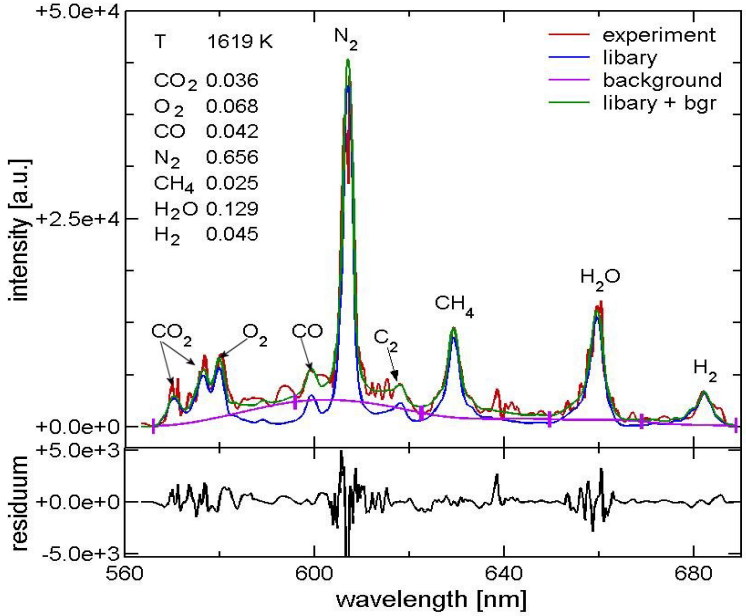


Raman spectroscopy (3)

- Experimental setup

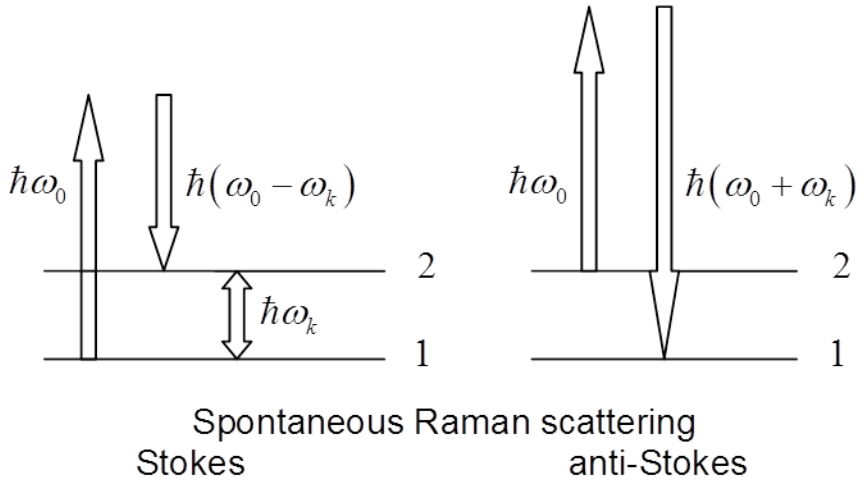


Low dispersion Stokes spectrum



Raman thermometry (1)

- Ratio of I_{Stokes} to $I_{anti\text{-}Stokes}$



$I_{stokes} \sim N_1$

$I_{anti\text{-}stokes} \sim N_2$

$$T = \frac{E_2 - E_1}{k \ln\left(\frac{N_1 g_2}{N_2 g_1}\right)}$$

- Typically applied for vibrational levels

→ Example N_2: Temperature sensitivity starting from ~ 500K (otherwise too low fractional population)

→ Not very common in combustion community

Raman thermometry (2)

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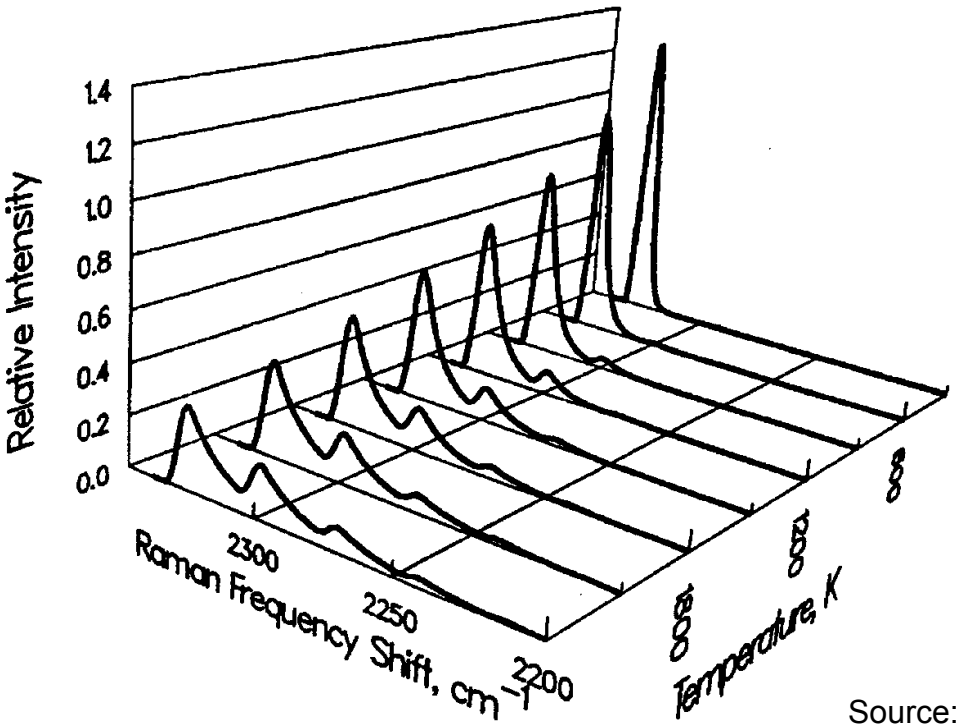
- Measure entire **Raman Stokes** spectrum
- Combustion: Typically ro-vibronic spectrum of N_2
- **High** dispersion → resolve only N_2, no other molecules

Not very common in combustion research (high dispersion comes along with low signal)



Source: Abacus

Pure Raman thermometry not common in combustion community

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Coherent anti-Stokes Raman spectroscopy (1)

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- Non-linear polarization $P_i = \varepsilon_0 \left(\chi_{ij}^{(1)} E_j + \chi_{ijk}^{(2)} E_j E_k + \chi_{ijkl}^{(3)} E_j E_k E_l + \ldots \right)$

$\approx 10^{0}$ $\quad \approx 10^{-12}$ $\quad \approx 10^{-23}$

P_i : Polarization

E_i : Electrical field

$\chi^{(n)}$: Susceptibility of n-th order

⇨ Non-linear effects are observable only at high electrical field strength

⇨ Pulsed LASER is prerequisite

In Gases : $\chi^{(2)} = 0$

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CARS: theoretical background

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- Wave equation describes light emission due to non-linear polarization

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \vec{P}}{\partial t^2}$$

Here: $P_i = \varepsilon_0 (\chi_{ij}^{(1)} E_j + \chi_{ijkl}^{(3)} E_j E_k E_l)$

$$E_{(\omega_4)} \propto E_{(\omega_1)} E_{(\omega_2)} E_{(\omega_3)} \left| \chi_{CARS_{(\omega_1,\omega_2,\omega_3)}} \right|^2 \frac{e^{(i\Delta kl)} - 1}{\Delta k}$$

coherent

Common practice in CARS: $\omega_1 = \omega_3$

$$I_{CARS} \propto I_1^{\,2} I_2 \left| \chi_{CARS_{(\omega_1,\omega_2)}} \right|^2 l^2 \left(\frac{\sin\frac{\Delta kl}{2}}{\frac{\Delta kl}{2}} \right)^2$$

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CARS: energy and momentum conservation

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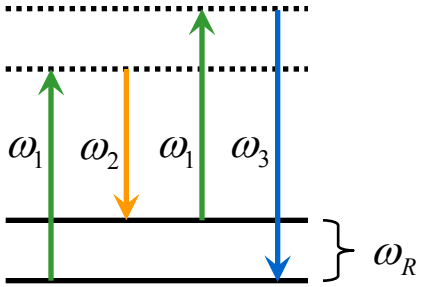
- Pictorial view of CARS

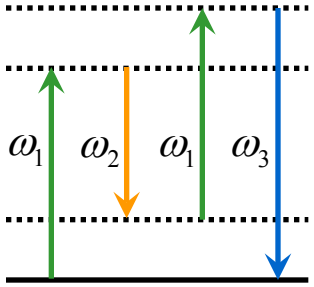
Energy balance: $\omega_3 = 2\omega_1 - \omega_2$

Pump laser

Stokes laser

CARS signal (anti-Stokes)



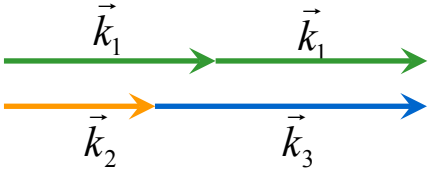


Selection rules

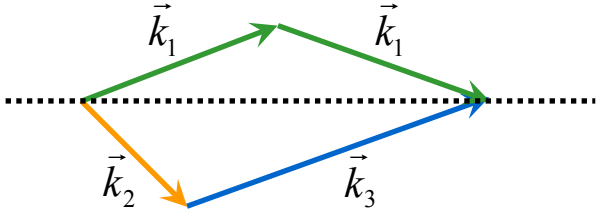
$\Delta J = 0, \pm 2$

$\Delta v = 1$

Momentum balance: $\vec{k}_3 = \vec{k}_1 + \vec{k}_1' - \vec{k}_2$ **Termed phase matching**



Co-linear CARS



BOX CARS: preferred, higher spatial resolution

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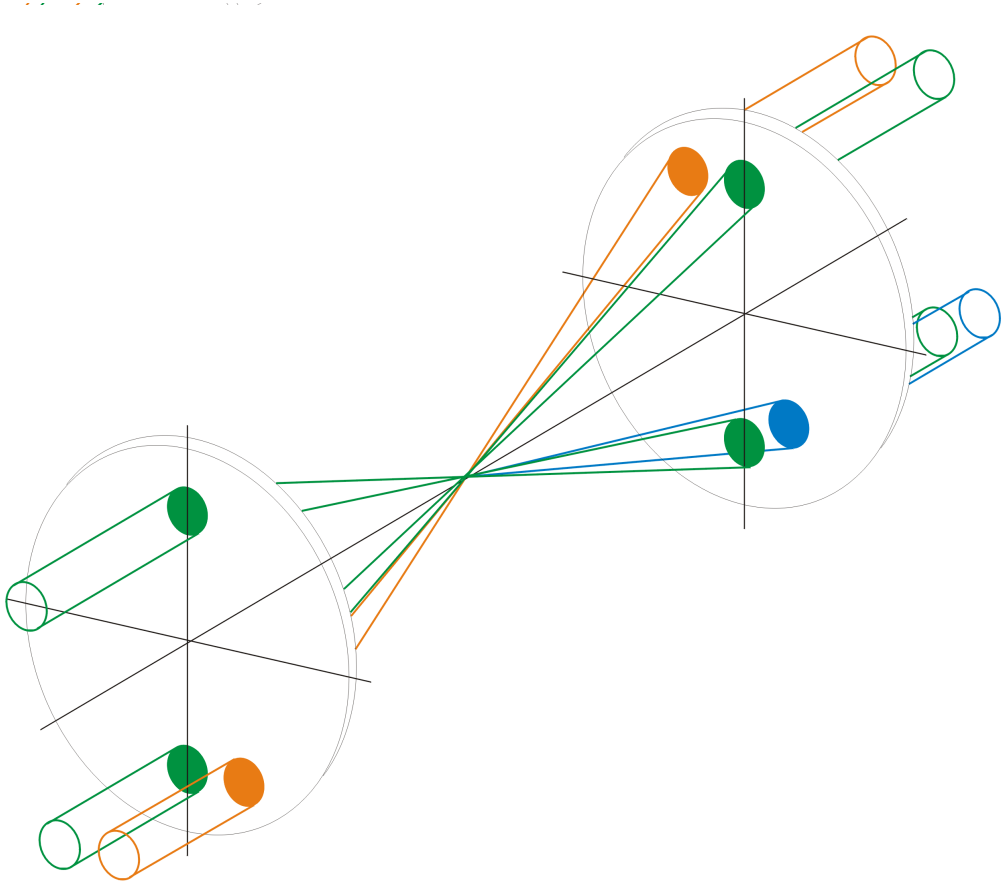
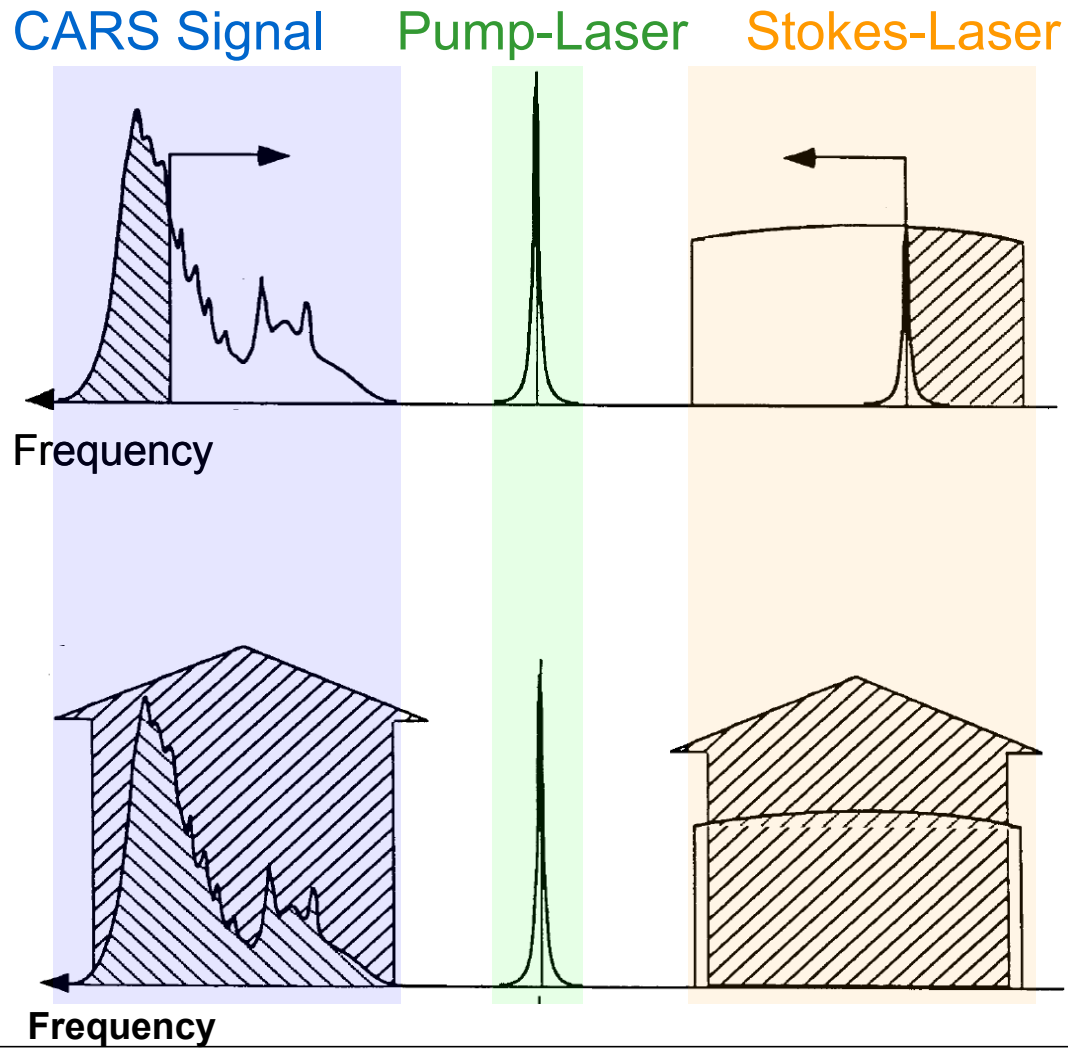
CARS: phase matching

- Realization of phase matching
  - **Pump laser: 532 nm (frequency-doubled Nd:YAG)**
  - **Stokes laser: 607 nm (broadband dye laser)**
  - **CARS signal: 473 nm**



CARS: broad band and scanning



Scanning CARS

Takes time

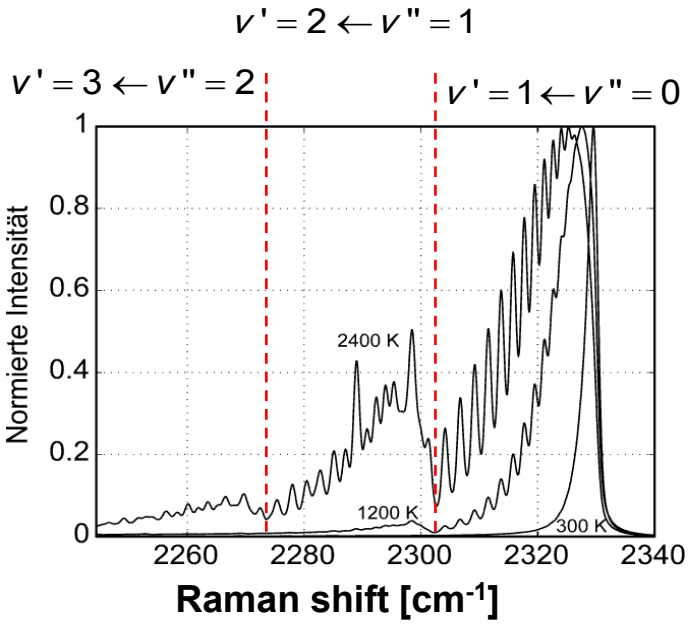
Not suitable for single-shot thermometry

Broadband CARS

→ **Single-shot thermometry**

CARS: thermometry

- Typical application in turbulent flames: ro-vibronic N_2-broad band CARS



⇨

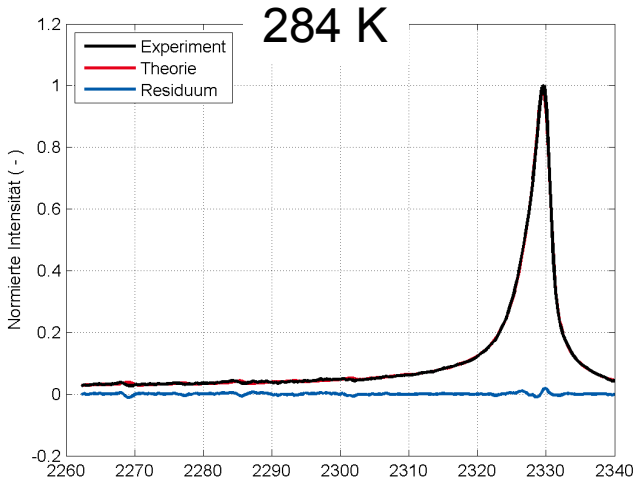
Temperature obtained by fitting CARS spectrum to experimental spectrum

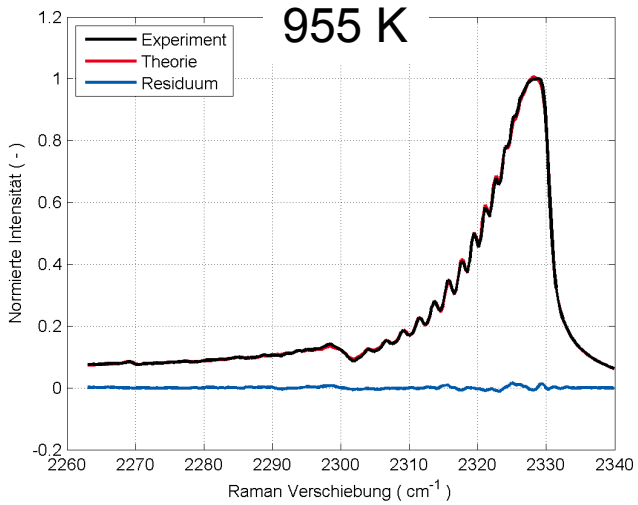
Temperature information is contained in line-strength~N_i^2 (in χ^3-tensor)

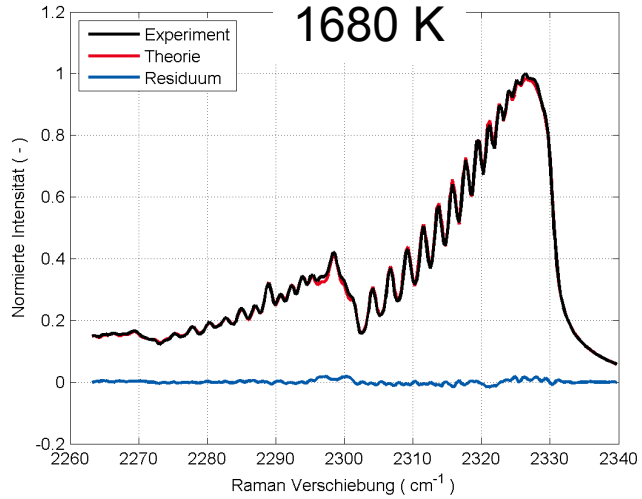
Based on Boltzmann distribution

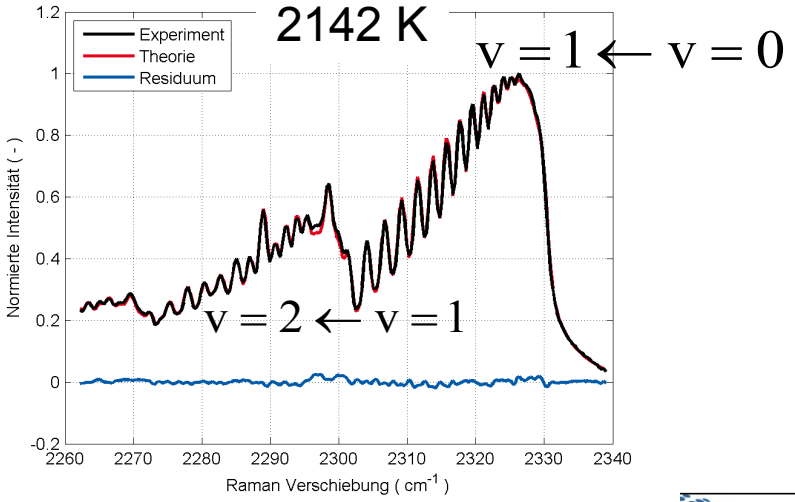
$$\frac{N_i}{\sum_i N_i} = \frac{g_i e^{-E_i/kT}}{\sum_i g_i e^{-E_i/kT}}$$

CARS: single shot spectra and spectral fit









CARS: experimental setup, combined with CO-LIF

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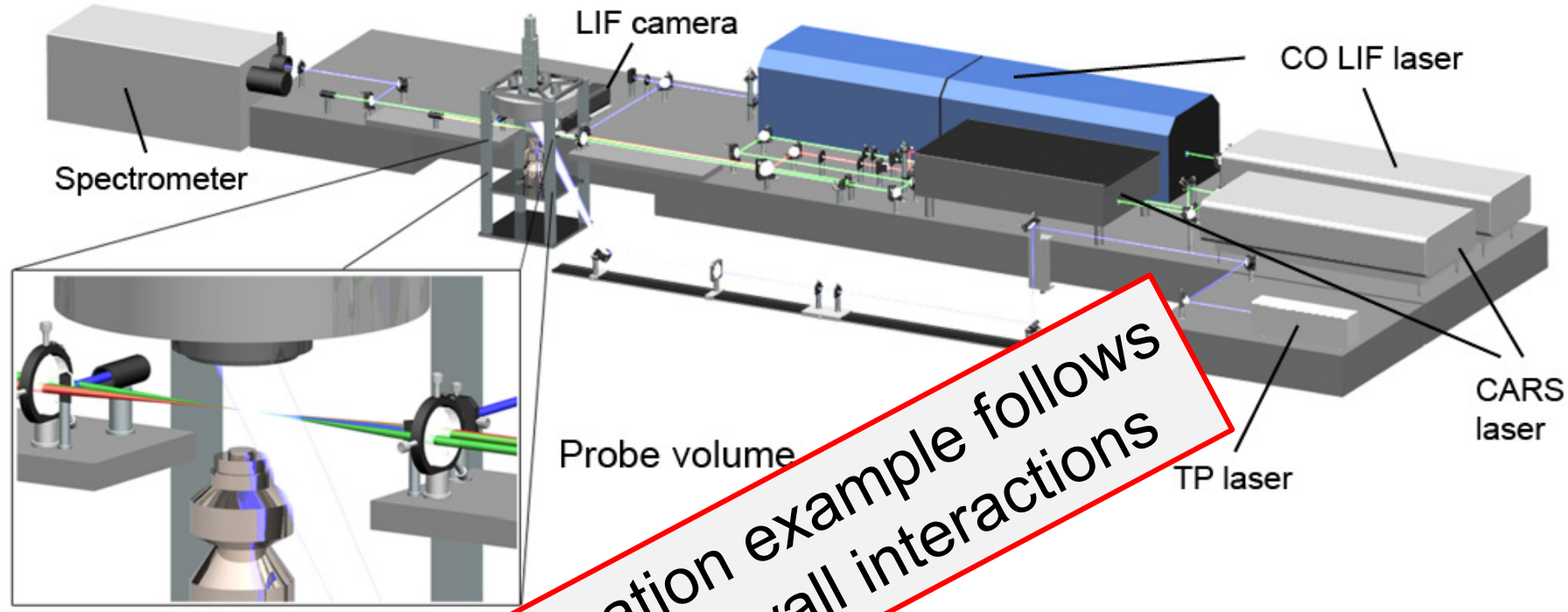

Application example follows in flame-wall interactions

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CARS: pro and con

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Advantages:

- precise single-shot temperature measurement of gas phase
- coherent signal allows detector placed far away from combustor
- No calibration required

Disadvantages:

- complicated optical setup
- spatial resolution in mean beam propagation direction only ~0.5mm, often worse
- mostly point-measurements (new fs/ps CARS allows for 1D and 2D CARS!!)

Spectroscopic methods – classification

- Based on
  - Boltzmann distribution

$$\frac{N_i}{N} = \frac{g_i \exp\left(-E_i / kT\right)}{\sum_j g_j \exp\left(-E_j / kT\right)} = \text{unique function of } T$$

g_i: degeneracy factor E_i: energy quantum state; both from quantum mechanics

  - Temperature-dependent absorption/emission

  - Density measurements via equation of state

$$pV = NkT \rightarrow T = \frac{pV}{Nk}$$

Temperature dependent emission/absorption

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- **Fluorescence tracer** added to gas
  - Typical tracers
    - Hydrocarbons: **aromates**, **ketones or aldehydes**
    - **Atoms**
- **Pro**
  - Tracer and its spectroscopic characteristics can be chosen in dependence of measuring task
- **Con**
  - Hydrocarbon tracer is thermally decomposed for T > ~700 K, not applicable in flames, but for example compression stroke in IC engine
  - Tracer may influence chemical and physical properties of the fluid
  - Spectroscopic properties of tracer often **not independent** of surrounding gas phase

Typical tracers for LIF thermometry

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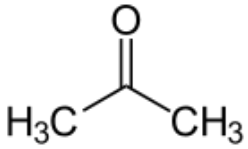
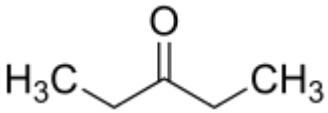
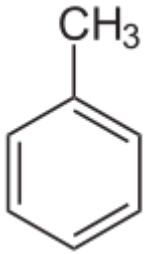
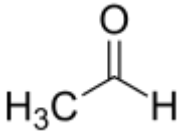
- Ketones:
  - acetone 
  - 3-pentanone 
- Aromates: toluene 
- Aldehydes: acetaldehyde 
- List is not complete: search for LIF-tracers with higher quantum yield, less O_2-quenching, etc. goes on

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Classification of LIF-thermometry

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- Two options
  - **Two line** excitation **– one color** detection: excite tracer at two different wavelengths (two lines) and measure fluorescence broadband (one color)

  → Exploit temperature dependent **absorption** band
  - **Single line** excitation **– two color** detection: excite tracer at one wavelength (single line) and measure fluorescence at two spectrally separated bands (two color)

  → Exploit temperature dependent **emission** band

3-pentanone LIF thermometry

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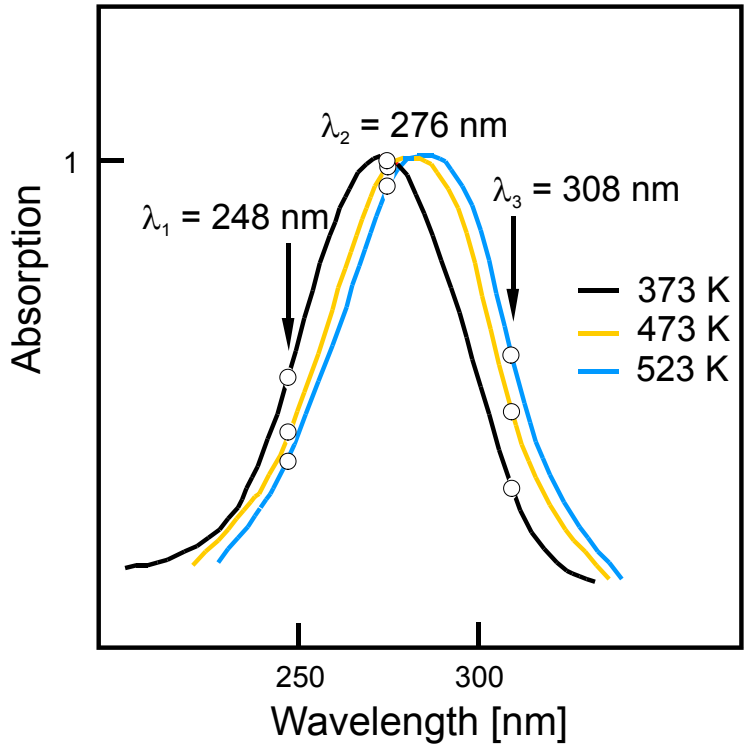
- 3-pentanone: Example for **two line – one color** thermometry



- Spectra are normalized
- total integral increases with temperature
- Two lasers/two cameras needed
- For more information see Schulz, Dreizler, Ebert, Wolfrum Combustion Diagnostics, Springer Verlag 2007

$$\frac{S_1(\lambda_1,p,T)/I_{Laser_1}(\lambda_1)}{S_2(\lambda_2,p,T)/I_{Laser_2}(\lambda_2)}\frac{\pi_2}{\pi_1}=\frac{\sigma_1(\lambda_1,T)}{\sigma_2(\lambda_2,T)}\frac{\phi_1(\lambda_1,T)}{\phi_2(\lambda_2,T)}=F(T)$$

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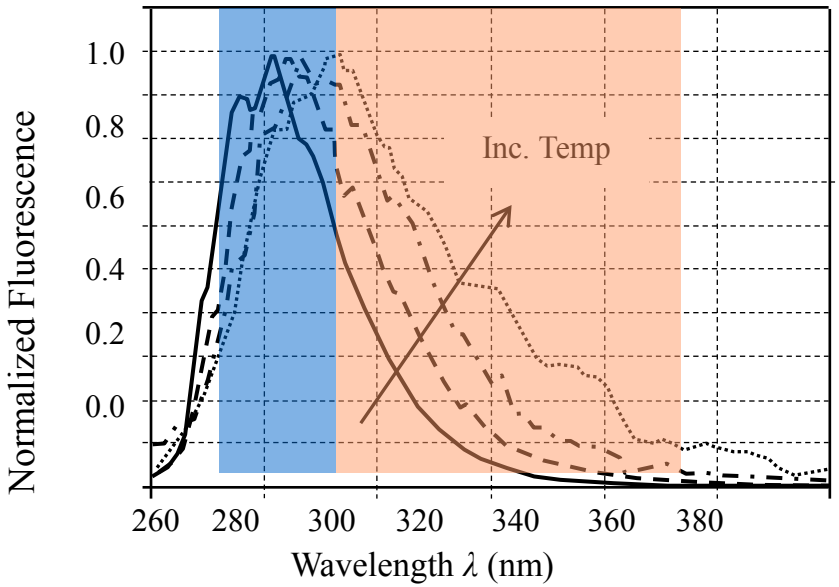
Toluene LIF thermometry

- Toluene: Example for **single line – two color** thermometry



- Spectra are normalized
- Strong quenching by O_2 → reducing high quantum yield compared to oxygen-free atmosphere
- For more information see Peterson, Baum, Böhm, Dreizler, Appl. Phys. B 2014

Application example follows at end of this chapter

Spectroscopic methods – classification

- Based on
  - Boltzmann distribution

$$\frac{N_i}{N} = \frac{g_i \exp\left(-E_i / kT\right)}{\sum_j g_j \exp\left(-E_j / kT\right)} = \text{unique function of } T$$

g_i: degeneracy factor E_i: energy quantum state; both from quantum mechanics

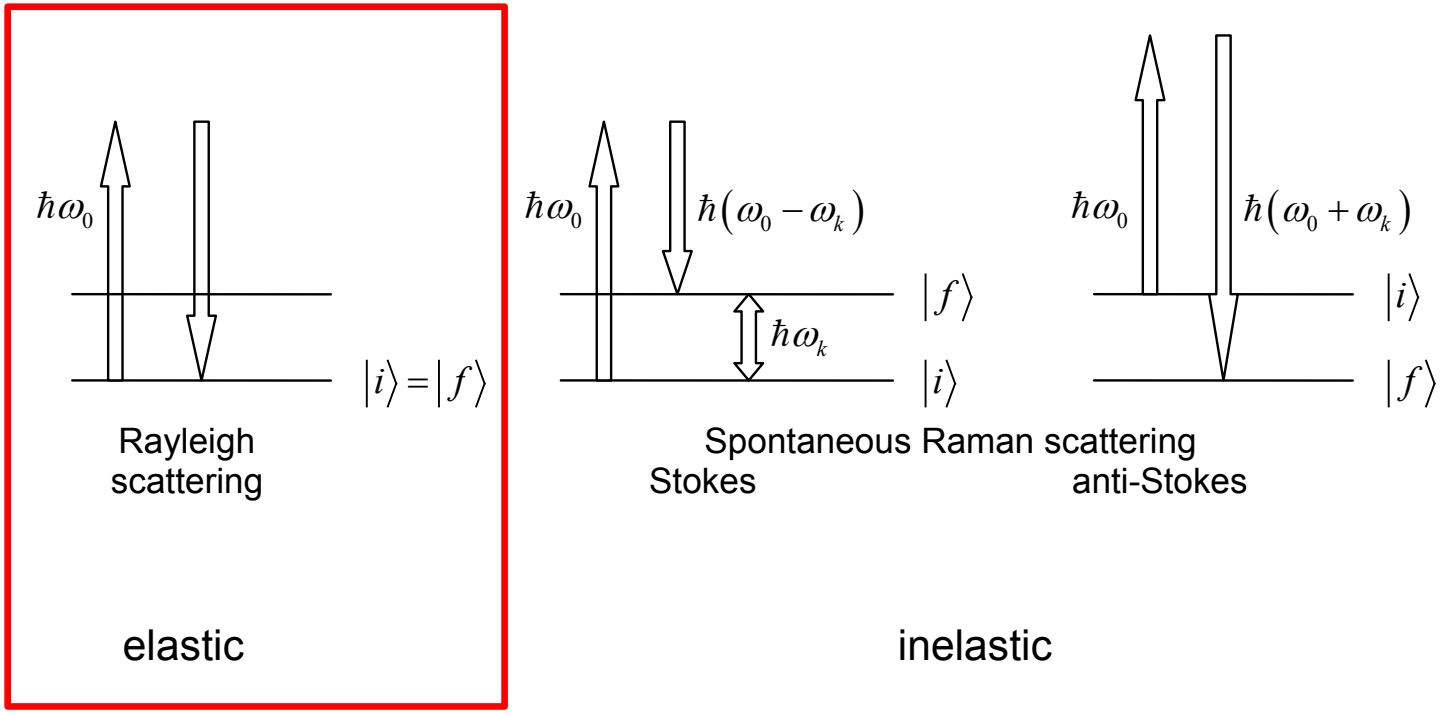
  - Temperature-dependent absorption/emission

  - Density measurements via equation of state

$$pV = NkT \rightarrow T = \frac{pV}{Nk}$$

Rayleigh spectroscopy – in combination with Raman if gas composition unknown

- Elastic and inelastic light scattering of photons off molecules



Rayleigh thermometry: known gas comp.

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- Rayleigh signal intensity $F_{ray}(x) = C_{calib}\,\sigma_{ray}\,I_{laser}(x)\,N/V$

- With **known Rayleigh cross-section σ_{ray}**(known gas mixture, no reactions), measured laser intensity, and calibration Ray-signal proportional to local gas density
- Deduce temperature in combination with equation-of-state
- Example: ideal gas law $pV = NkT$

$$\rightarrow T = \frac{pV}{Nk} = \frac{p \cdot C_{calib} \cdot \sigma_{Ray} \cdot I_{laser}(x)}{k \cdot F_{Ray}(x)}$$

- Wavelength-dependent Ray cross section of gas *i* can be calculated from index of refraction

$$\sigma_{ray,i} \cong \frac{4\pi^2 (n_i - 1)^2}{(N_A / V)^2 \lambda^4}$$

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Rayleigh thermometry: unknown gas comp.

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- Rayleigh signal intensity $F_{ray}(x) = C_{calib}\,\sigma_{ray}\,I_{laser}(x)\,N/V$

- Measure laser intensity and perform calibration Ray-signal proportional to local gas density
- **Gas mixture unknown** (for example due to chem. reactions or mixing)

  → gas composition must be measured

  → **simultaneous Raman** scattering
- Once gas composition is known, effective Rayleigh cross-section can be calculated by:

$$\sigma_{ray} = \sum_i x_i \sigma_{ray,i}$$

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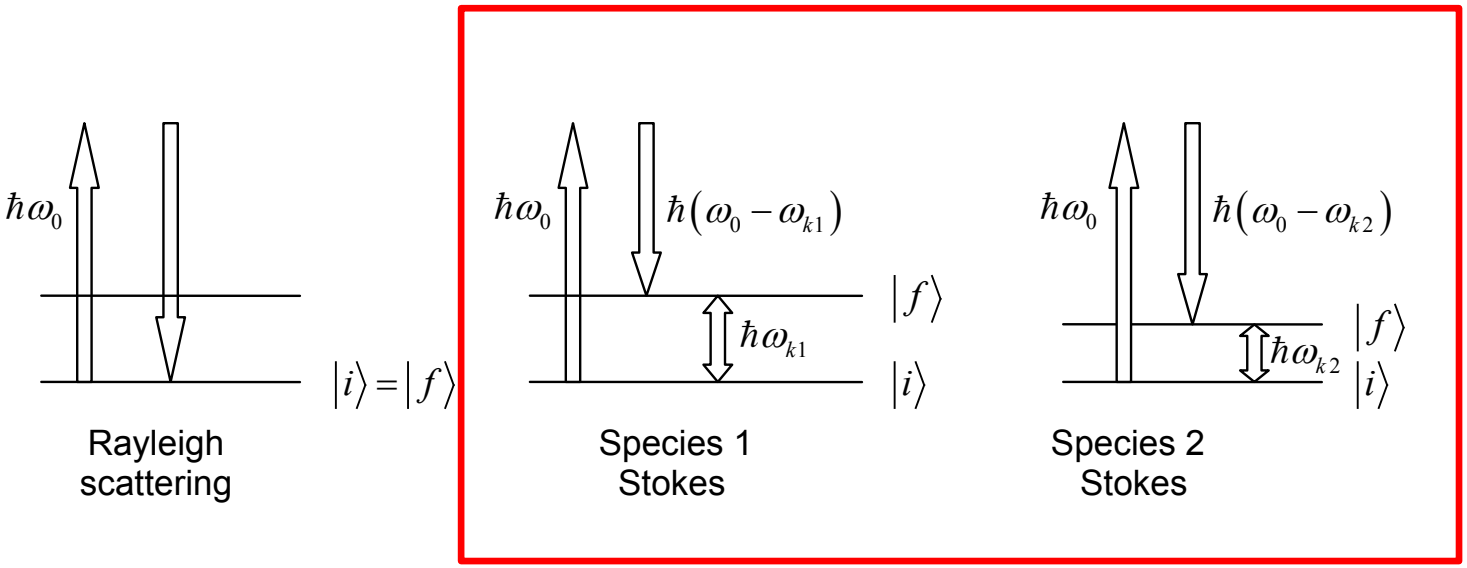
Raman/Rayleigh spectroscopy (1)

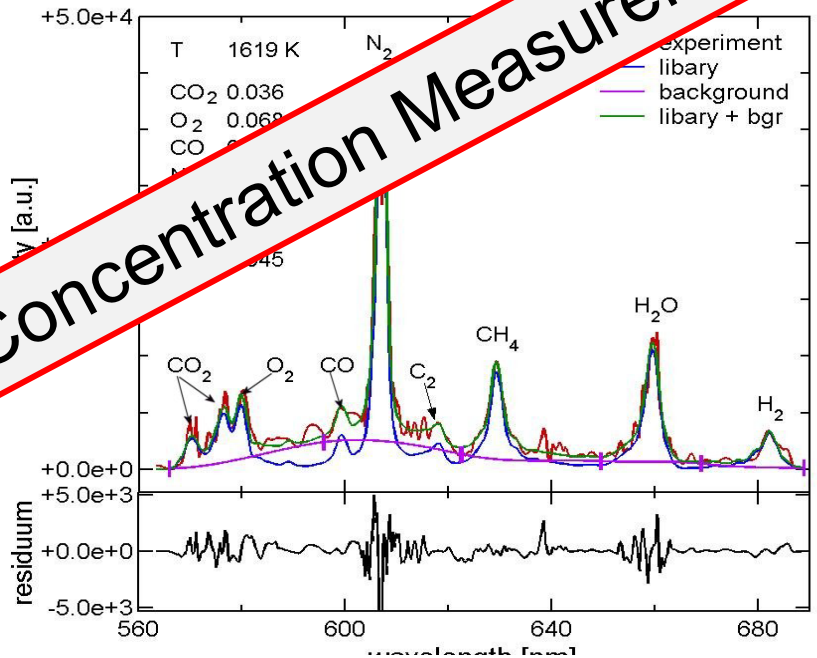
- Measure entire Raman Stokes spectrum
- **Low** dispersion → measure multi-scalars and deduce temperature either from Rayleigh scattering (see below) or from absolute gas density
- **Multi-scalar**: exploit different energy separation between quantum states for different molecules



Raman/Rayleigh spectroscopy (2)

- Measure entire Raman Stokes spectrum with **low** dispersion

- Ram in combination with Ray common for studying details of **open flames** but Ram used then for conc. measurements
- Ram for thermometry via gas density used **in confined flames** in combination with conc. measurements



See chapter 7 Gas Concentration Measurements

Simultaneous Raman/Rayleigh spectroscopy

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- Raman scattering → species concentrations $N_i(r)$

$$S_{ram,i}\left(\vec{r}\right) \propto \sigma_{ram,i}\left(T\left(\vec{r}\right)\right) I_{Laser} \; N_i\left(\vec{r}\right)$$

- Rayleigh scattering → density, with EOS → temperature $T(r)$

$$S_{ray}\left(\vec{r}\right) \propto \sigma_{ray}\left(N_i\left(\vec{r}\right)\right) I_{Laser} \sum N_i\left(\vec{r}\right)$$

$$\sigma_{ray} = \sum_i \left(\frac{N_i\left(\vec{r}\right)}{\sum_j N_j\left(\vec{r}\right)} \right) \sigma_{ray,i} \xrightarrow{\text{Ideal gas law (EOS)}} T\left(\vec{r}\right) \propto \frac{1}{\sum N_i\left(\vec{r}\right)}$$

- **Iterative procedure to determine temperature and species**

See chapter 7 Gas Concentration Measurements

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Motivation

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- Gas temperature is a leading parameter in combustion

- Internal combustion engines
  - Temperature dependencies
    - Mixture preparation
    - Ignition, auto-ignition
    - Combustion
    - Pollutant formation
    - Heat loss

- Measure and understand spatial and temporal evolution of unburned gas temperature in IC engine
- For details see: Peterson et al. PCI 2013

Temperature Fields in IC Engines

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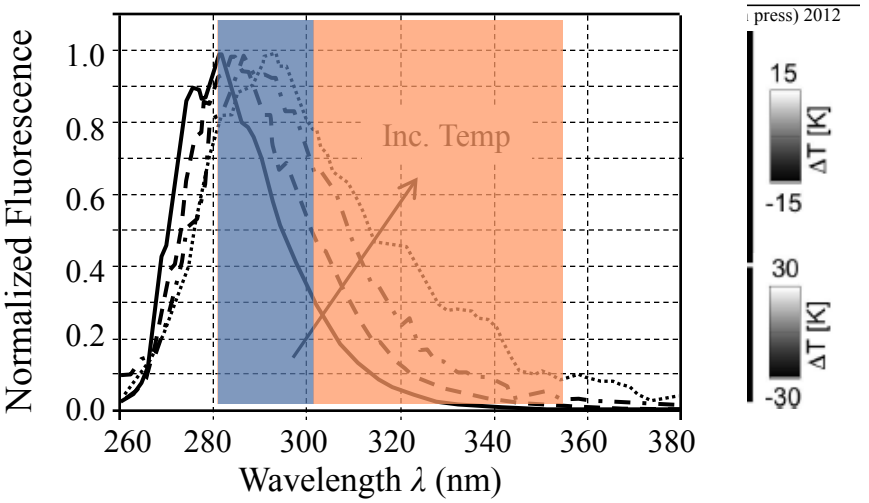
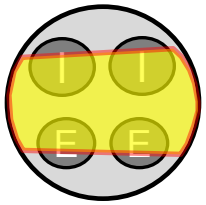
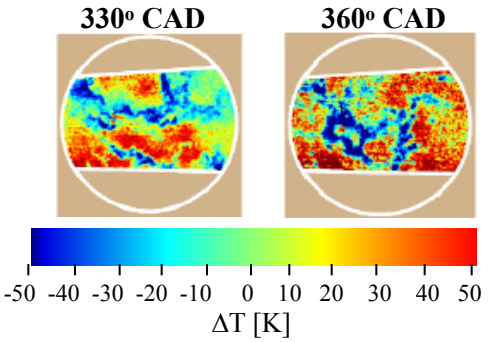
- Laser Induced Fluorescence (LIF) Thermometry
- Toluene LIF Thermometry
  - Single line excitation
    - *248 or 266 nm*
  - *Single* or *two* color detection
- IC Engines
  - Temperature stratification[1,2,3,4]
  - Low repetition rates
- Focus here
  - High-speed toluene LIF and PIV measurements
  - Temporal evolution of 2D temperature field



J.E. Dec and W. Hwang, *SAE Technical Paper* 2009-01-0650, 2009





1: Kakuho et al. SAE, 2006
2: Fujikawa et al. SAE, 2006
3: Hwang and Dec, *SAE*, 2009
4: Kaiser et al., *ProCI In Press*, 2012
5: Dronniou and Dec, *SAE*, 2012

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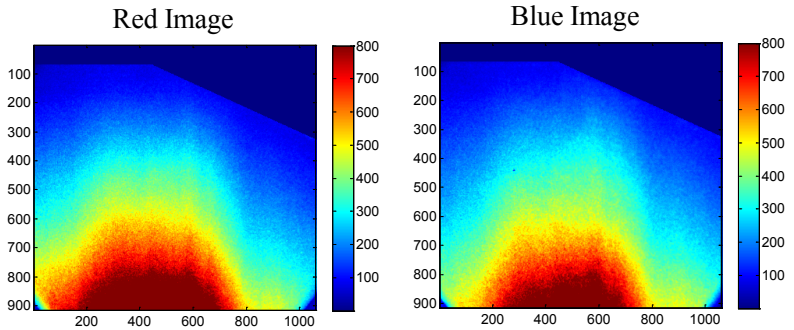
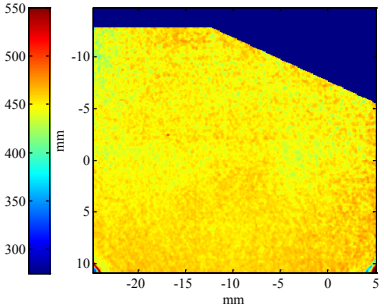
Experimental Setup

- High-speed imaging
- Toluene LIF
- 2D-PIV
- Two-color fluorescence detection

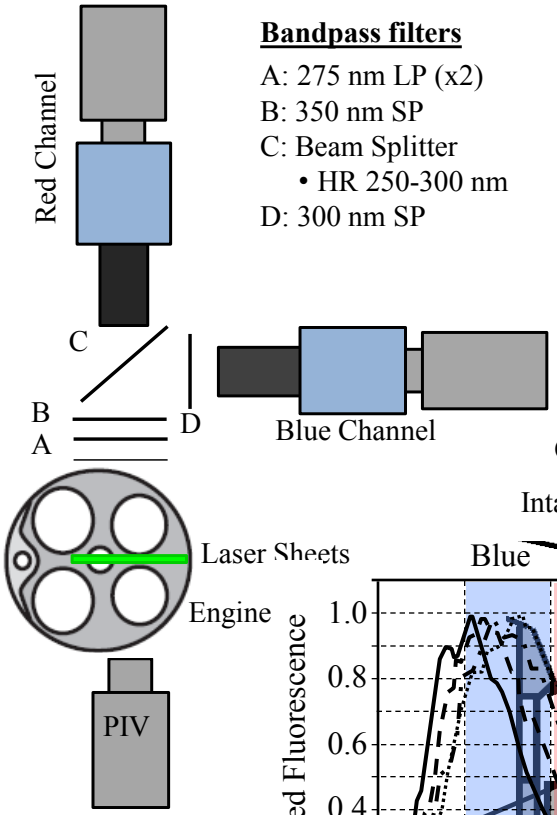


- HS-IRO CMOS



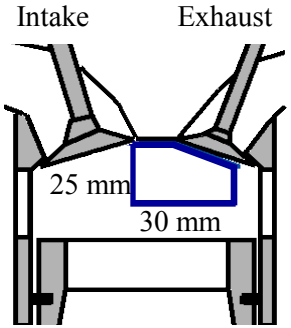
- Laser sheets centralized
- Image through quartz

- T-LIF independent:
  - Absorption
  - Laser fluence
  - Mixture inhomogeneities

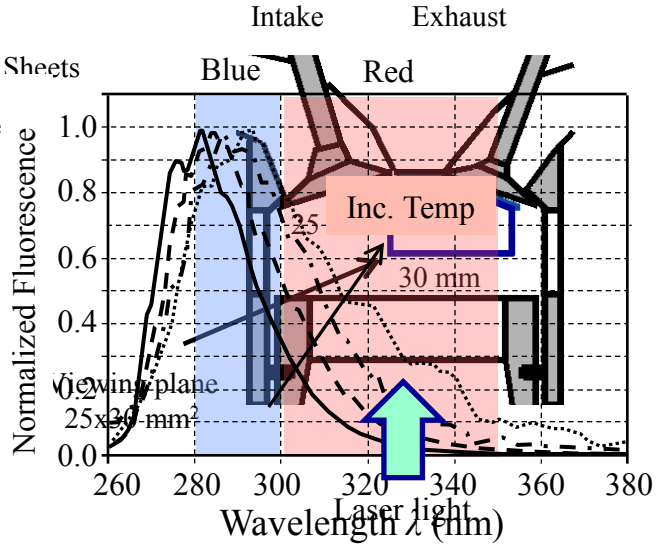


Bandpass filters

A: 275 nm LP (x2)
B: 350 nm SP
C: Beam Splitter
• HR 250-300 nm
D: 300 nm SP



Optical Engine



Experimental Setup

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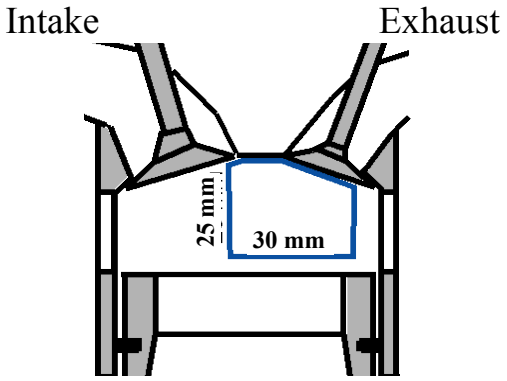
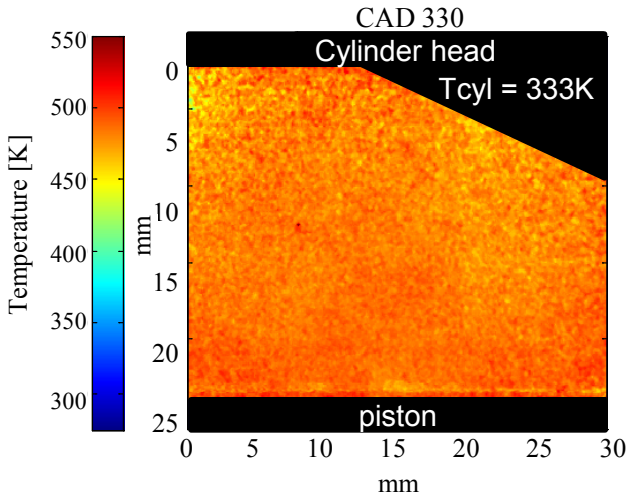
- Field-of-view
  - 25x30 mm² region
  - Offset from cylinder axis
  - Near cylinder head
  - Cylinder head
    - Set temperature: 333K
    - Expected thermal gradients near colder surfaces
- Images
  - 3x3 median filter
  - 3x3 pixel binning
  - Spatial resolution
    - 0.08 mm/pixel





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Engine Operating Conditions

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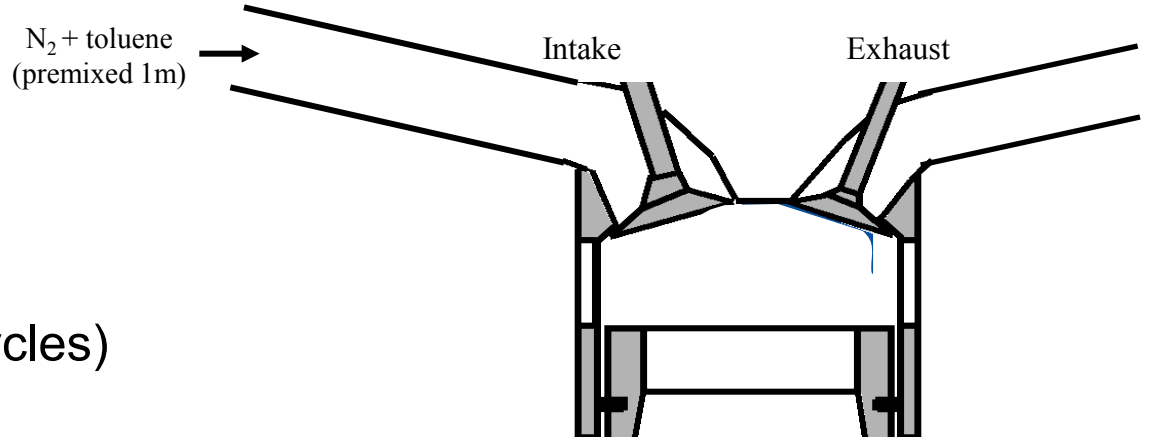
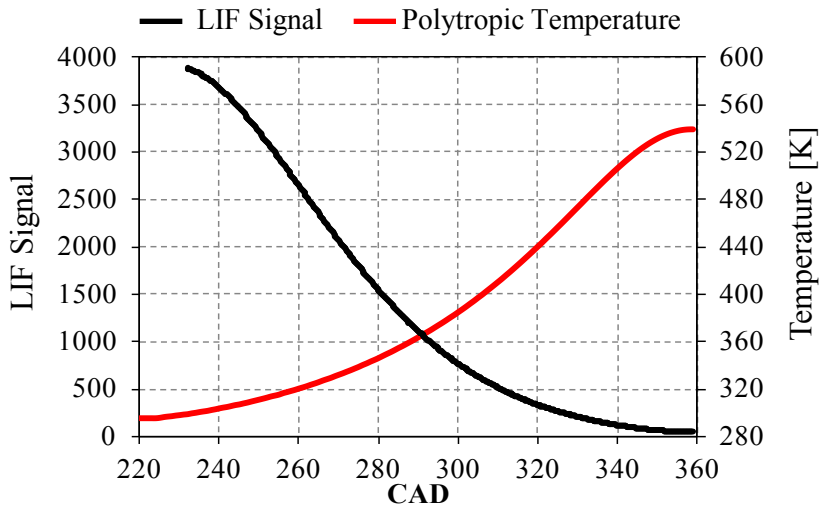
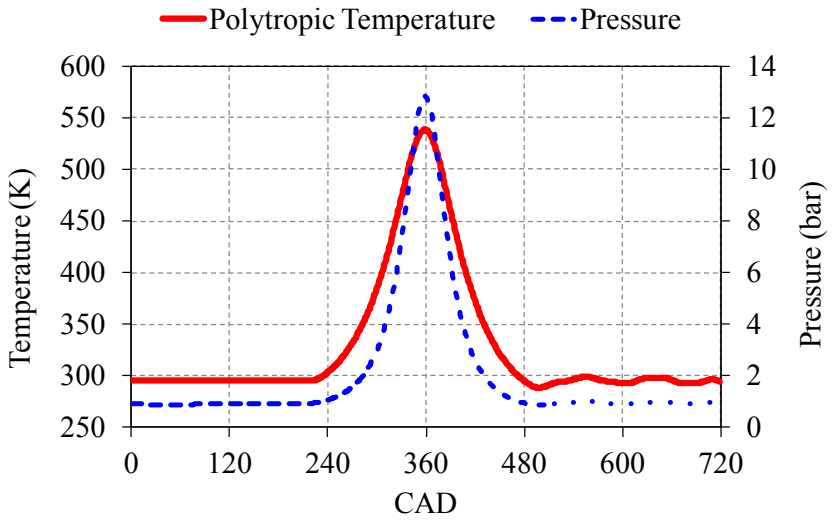
- 1000 RPM
- Intake
  - Nitrogen
  - Toluene vapor (2.5% vol.)
  - 95 kPa, 295K
- Motored Operation (72 cycles)
  - CR = 8.5
- LIF signal dynamic range







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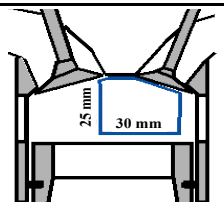
LIF Signal



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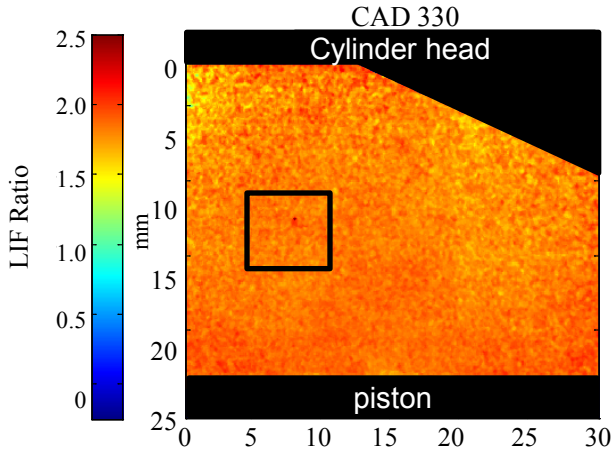
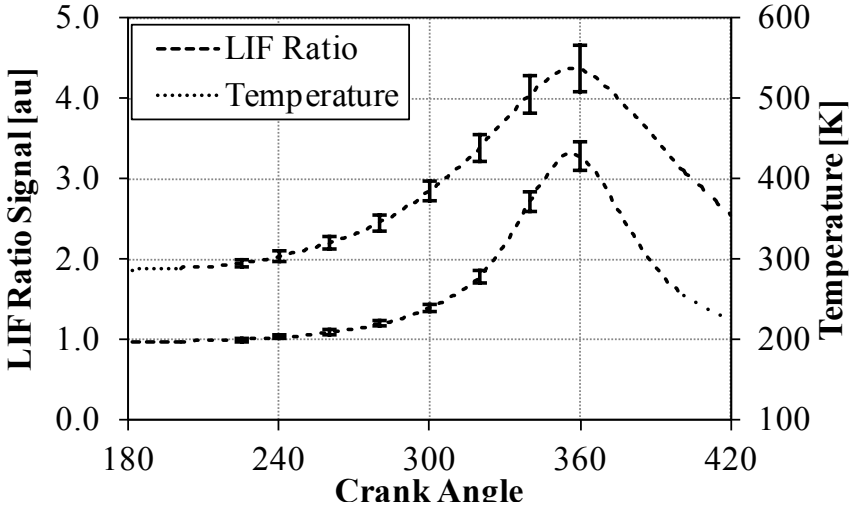
- Calibration (LIF → Temp)
  - LIF ratio (72 cycles)
    - 5x5 mm^2 region
  - Calibrate to polytropic temperature
- Precision Uncertainty
  - $LIF_{ratio,\ stdev}$ / LIF_{ratio}
  - Pixel-wise (0.08 x 0.08 mm^2 region)
  - LIF precision uncertainty
    - T = 295 ± 5 K (2%)
    - T = 540 ± 29 K (5.2%)
  - 10x10 pixel region
    - T = 540 ± 19K (3.5%)





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Temperature Images for fired operation

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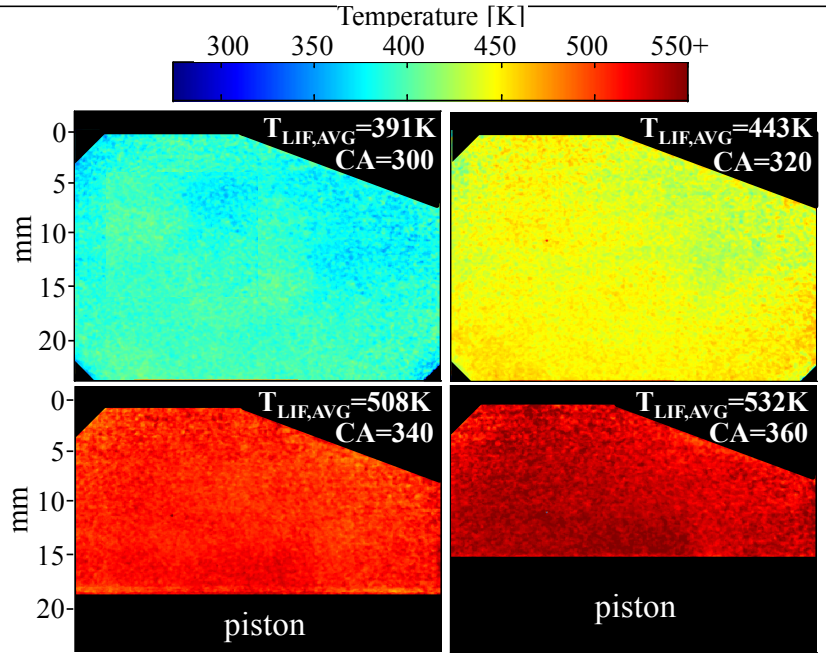
- Compression
  - Homogeneous temperature distribution
  - Temperature “structures” not present
- Expansion
  - Cold temperatures emerge from cylinder head
  - Out-gassing of crevice gases
  - Cold gas entrainment from right side
    - 50 K colder



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Temperature distributions

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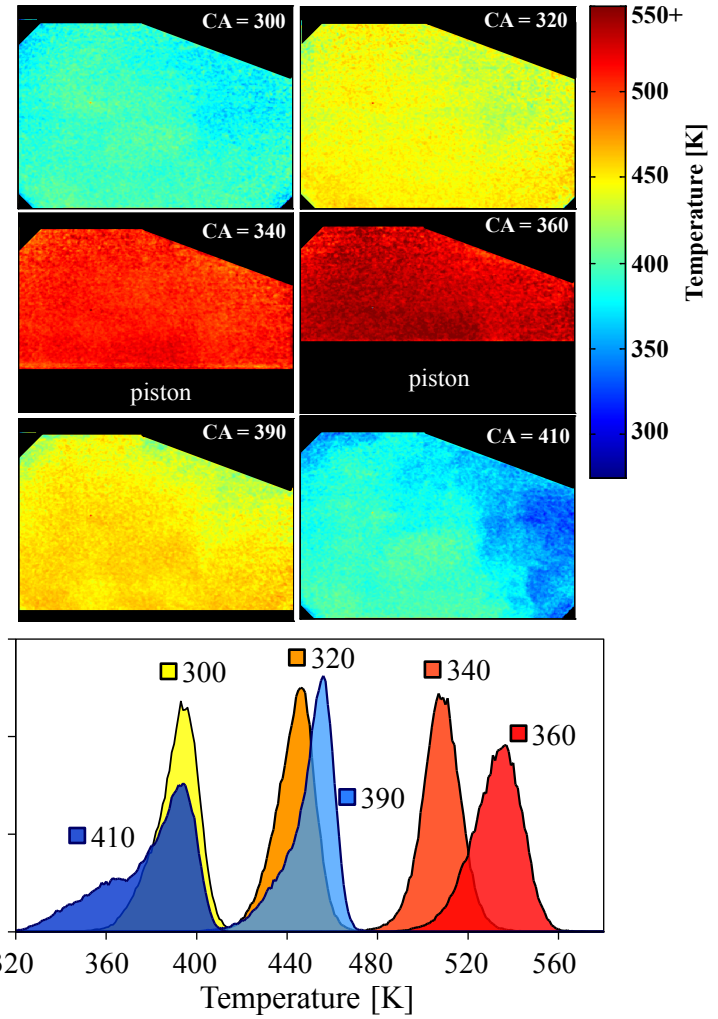
- Compression
  - Homogeneous temperature distribution
  - Gaussian-like distribution
- Expansion
  - Temperature inhomogeneities
  - Skew / bimodal distributions



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Temperature Distribution

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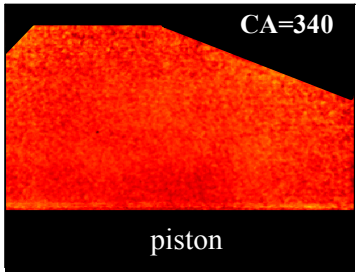
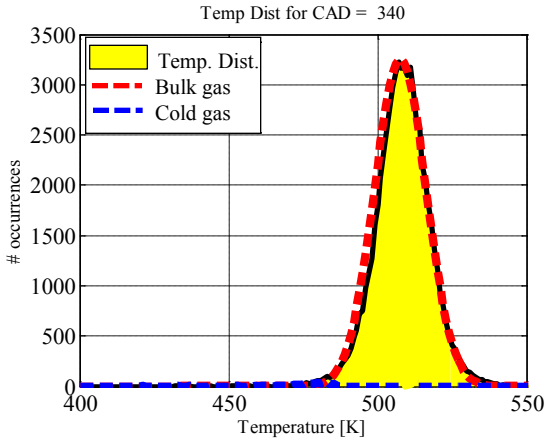
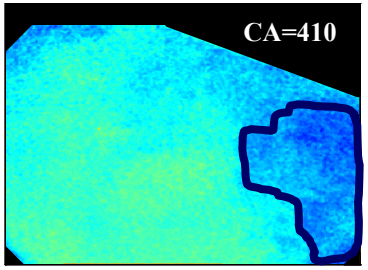
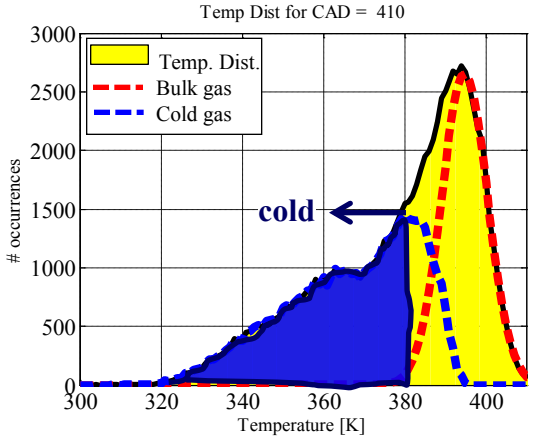
- Identifying temperature inhomogeneities
  - Cold gas
- Gaussian fit to bulk gas temperature
- Subtract from temperature distribution
  - Cold gas distribution
- Cold temperature inhomogeneities
  - < peak of cold gas distribution









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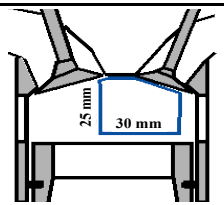
2D PDF Cold Temperature



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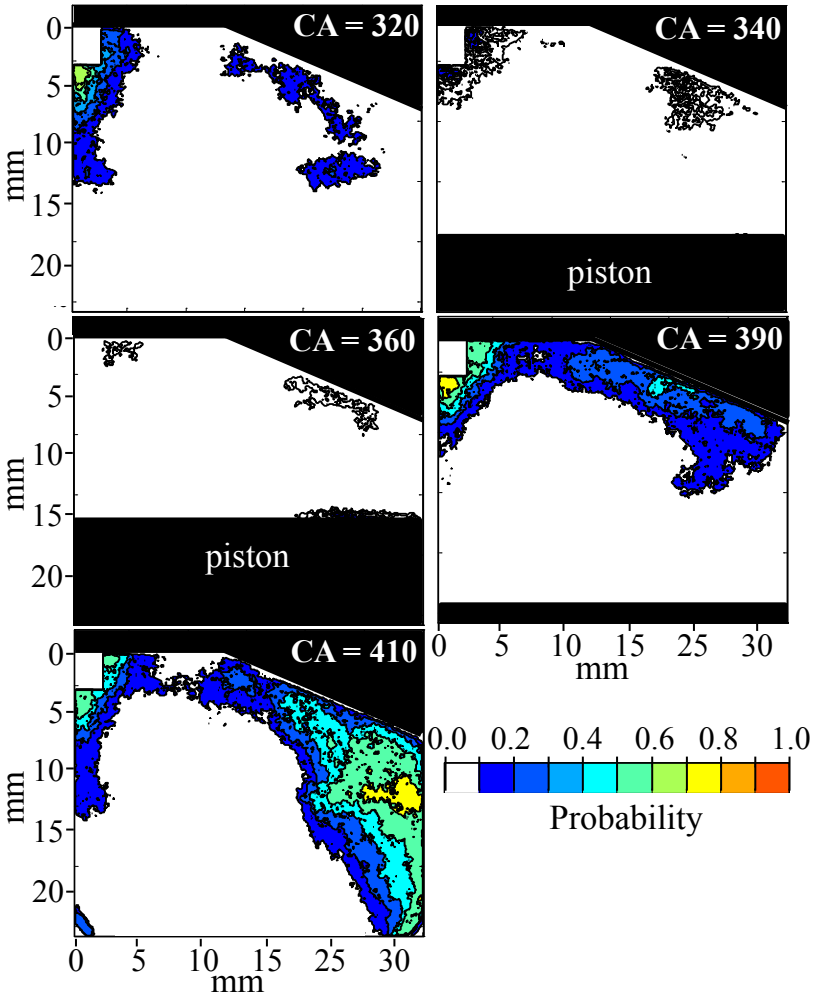
- 72 motored cycles
- Location, occurrence of cold temperature
- Compression
  - Colder temperatures near cylinder head
  - Low probability (< 30%)
  - Temperature boundary layer not visible
- Expansion
  - Cold regions near cylinder head
  - Cold gas enters viewing plane from crevices



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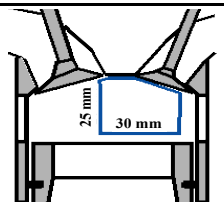
Cold Gas Expansion



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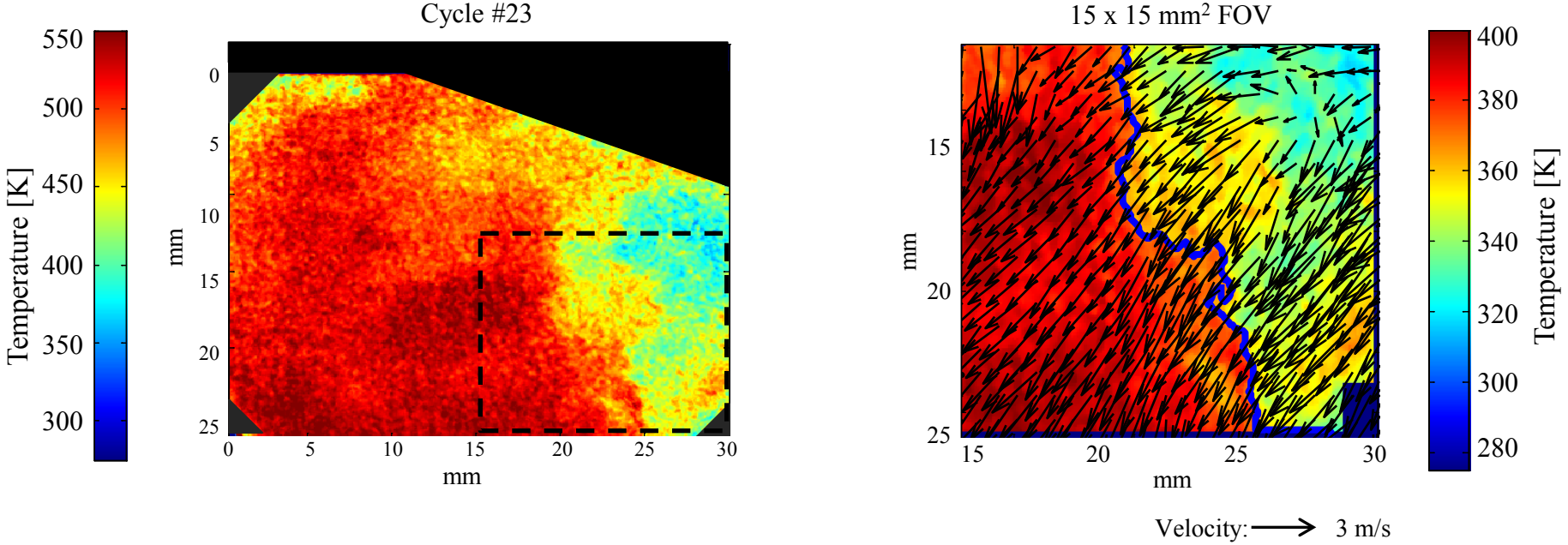
CAD = 411



Temperature and velocity field

cold temperature threshold

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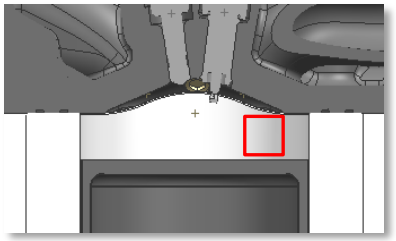
High speed toluene PLIF combined with PIV

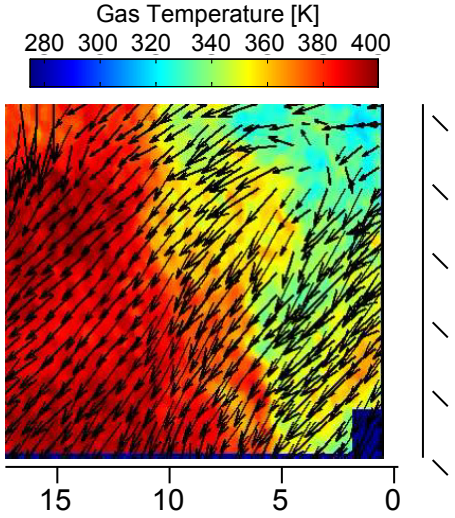
- Visualization of outgassing from crevices



Expansion CAD 410 – 430

Motored Operation

Cold gas outgassing from piston crevice



Peterson et al. *Proc. Combust. Inst*. 34, 3653-3660 (2013)

Conclusions temperature/velocity measurements in IC engine

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- High-speed Toluene-LIF and PIV to assess thermal transport in IC engine

- 2-color detection
  - LIF independent from absorption and local mixing
  - Precision uncertainty limited to 3-6% (dependent on temperature)

- Compression
  - Quasi-homogeneous temperature distribution

- Expansion
  - Evident colder gas evolution
  - Thermal stratification

- Cold front tracking
  - LIF vs. PIV
  - Transport of cold gas
  - Discrepancies
    - Out-of-plane motion

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Overall summary

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- Spectroscopic methods well suited for minimal invasive thermometry
- High resolution in time and reasonable resolution in space
- There is not the single method best suited for all tasks – choice depends on measurement task
- Optical access required – can be a problem
- High instrumental effort and expert knowledge needed

Chapter 6: Surface Thermometry – Thermographic Phosphors

TU Darmstadt, Germany
Dept. of Mechanical Engineering
Institute for Reactive Flows and Diagnostics

TECHNISCHE UNIVERSITÄT DARMSTADT

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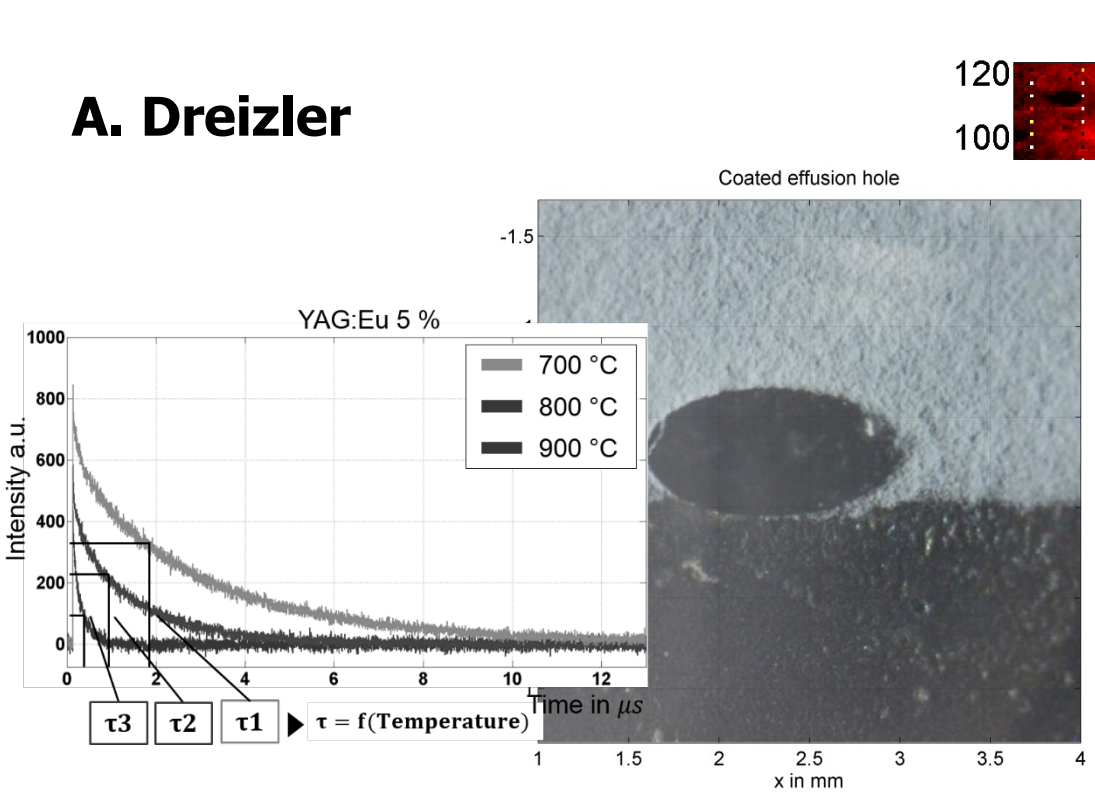
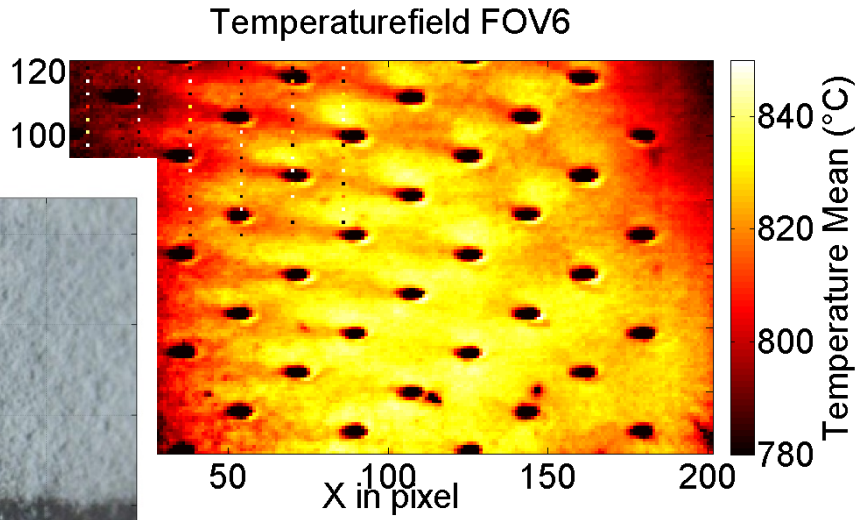
A. Dreizler





Outline phosphor thermometry

TECHNISCHE UNIVERSITÄT DARMSTADT

- Introduction & Motivation
- “Decay-Time Method” versus “Ratio Method”: comparing precision and accuracy
- Error treatment for decay-time method
- Application examples

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Surface temperature: diagnostics

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Thermocouples

- Invasive, limited spatial and temporal resolution, only point measurements

Pyrometry (Infrared thermometry)

- Emission coefficient generally unknown
- Sensitive against chemiluminescence and stray light

Temperature sensitive paints (TSP - coated), thermoliquid crystals (TLC)

- Temperature range < 380 K

Heat sensitive paints (HSP - coated)

- No temporal resolution

Thermographic phosphors (TGP – coated)

+ Broad temperature sensitive range (7 K -1870 K)

+ Insensitive against blackbody radiation, stray light and chemiluminescence

+ High spatial and temporal resolution, 2D diagnostics

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Thermographic Phosphors

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Thermographic phosphors:

- Rare-earth or transition metal doped ceramic materials
- Exploit temperature dependent spectroscopic properties following electronic excitation

Introduction & Motivation I

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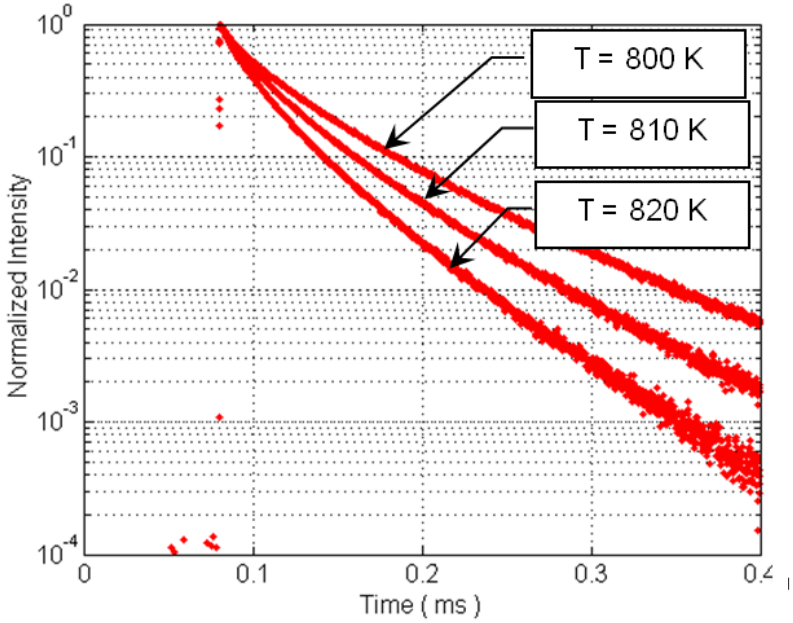
Principle of Phosphor Thermometry:

- Coat surface with thermographic phosphor
- Excite coating with UV-light source
- Detect emission with appropriate device either
  - time-resolved (fixed spectral range) or
  - Time-integrated and spectrally resolved (fixed temporal range)



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Introduction & Motivation II

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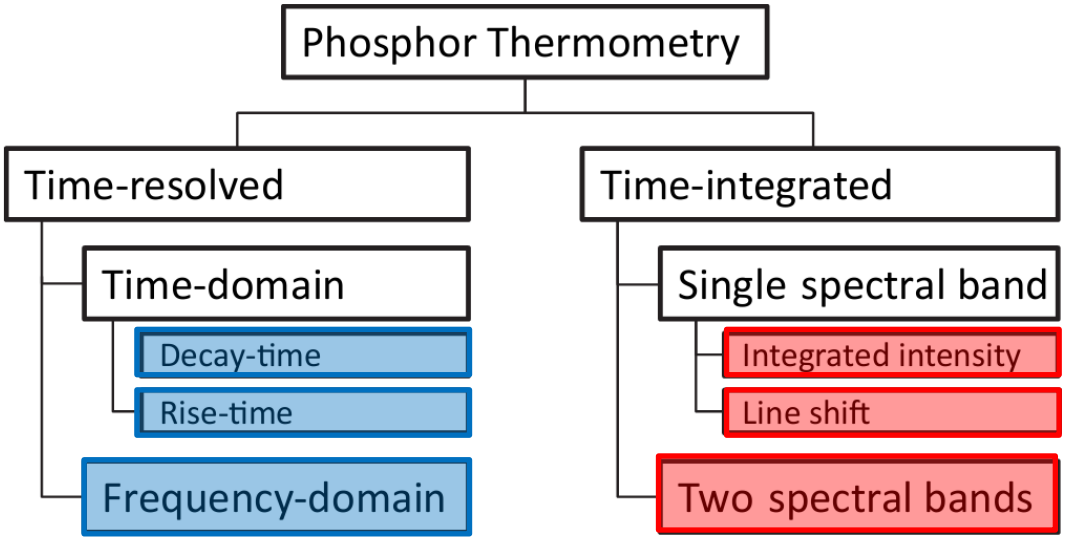
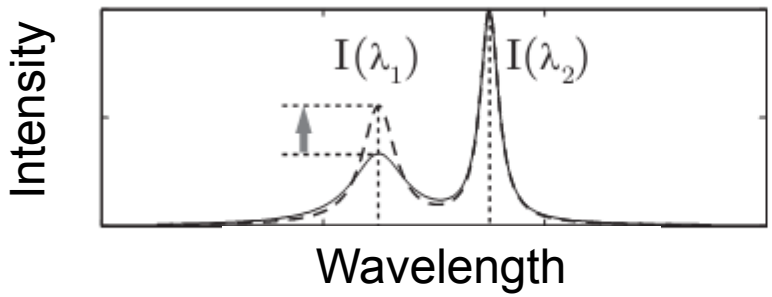
Approaches of Phosphor Thermometry





$$R = \frac{I(\lambda_1)}{I(\lambda_2)}$$

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Introduction & Motivation III

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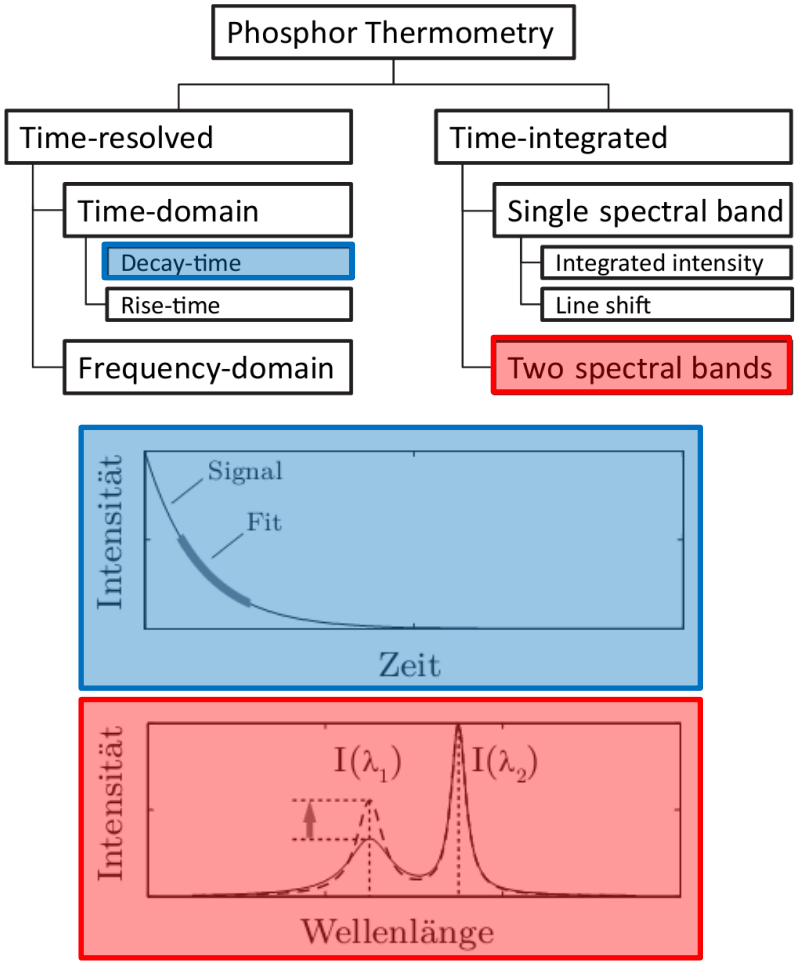
- Comparison of the two most popular approaches:
  - Luminescence Lifetime (Decay-time)
  - Intensity Ratio (Two-line)
- Motivation:
  - Decision support required for users
  - Comparison to highlight pros vs cons
  - Investigation of sensitivities, precision, accuracy and application
- Procedure
  - Use two CMOS high-speed cameras (same data-set)
  - Exemplified for phosphor which exhibits sensitivities in both approaches: Mg_4FGeO_6: Mn



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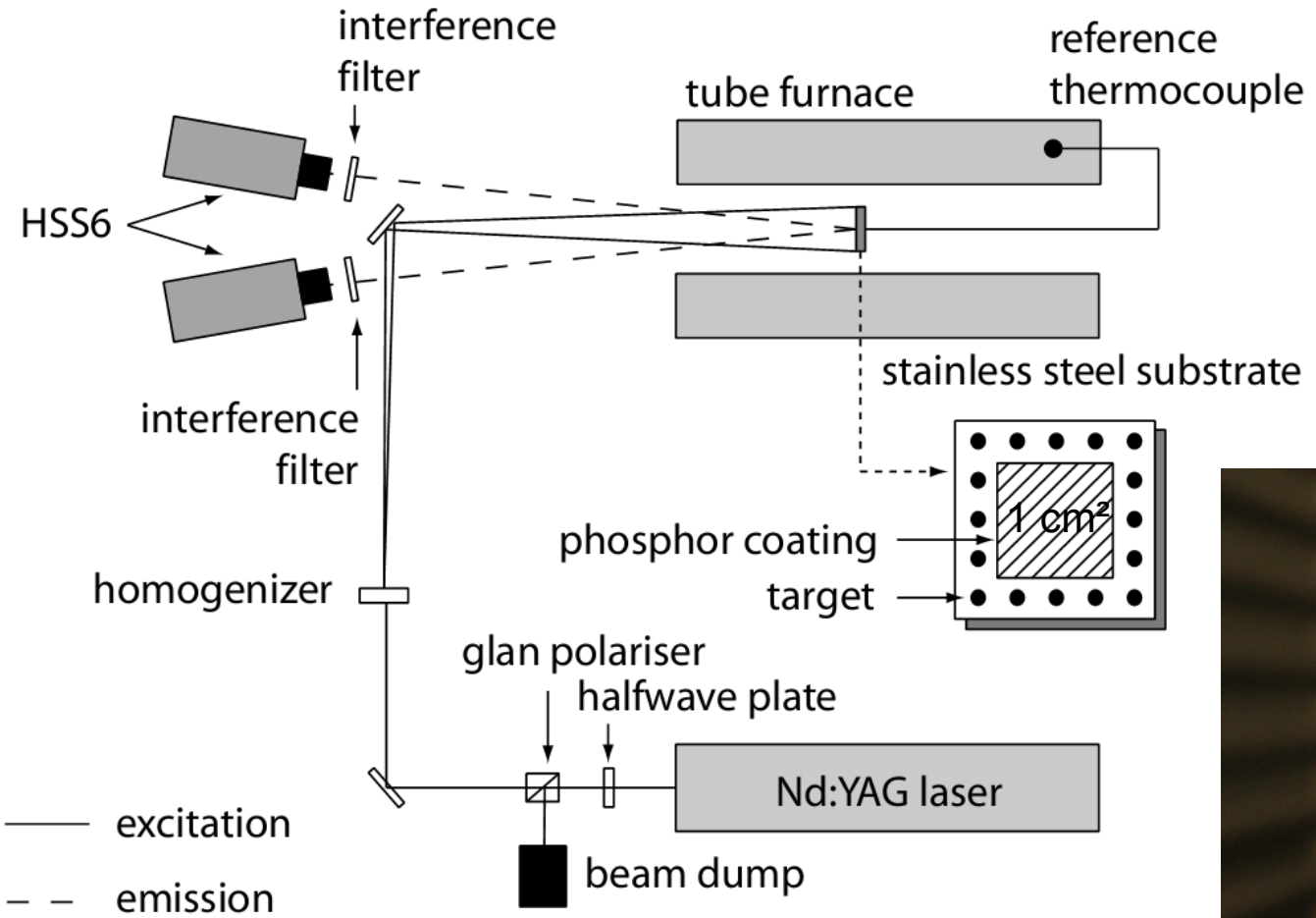
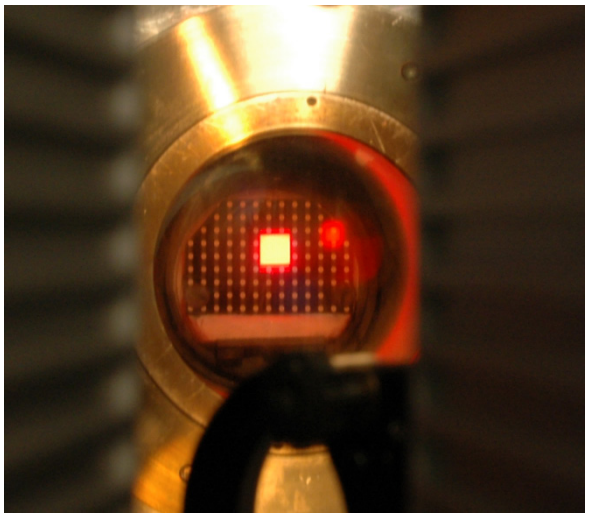
Experimental Setup



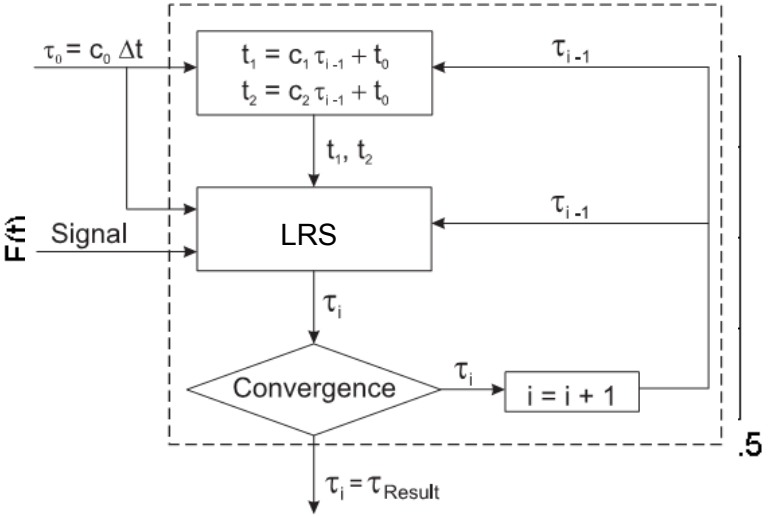


Data evaluation

- Nonlinearity intensity-correction of the CMOS Chip
- Image matching by pinhole model (Software: Davis 7)

Lifetime

- Pixelwise fitting of waveforms
- Brübach Algorithm + Linear Regression of the Sum (LRS)



Brübach, M. et al., Opt. Lasers Eng., 47 (1), 2008

Intensity ratio

- Pixelwise temporal integration:

$$R = \frac{\int_{t_1}^{t_2} I_{633\,\mathrm{nm}}(t)\,dt}{\int_{t_1}^{t_2} I_{660\,\mathrm{nm}}(t)\,dt}$$

- Two ratios R1 and R2 used:
  - R1: $t_1 = t_0 + 100\,\mu s$, $t_2 = t_0 + 120\,\mu s$ (corresponds to 1 image @50kHz)
  - R2: $t_1 = t_0 + 100\,\mu s$, $t_2 = t_0 + 1100\,\mu s$ (corresponds to 50 images @50kHz)

Results: Temperature dependent characteristics

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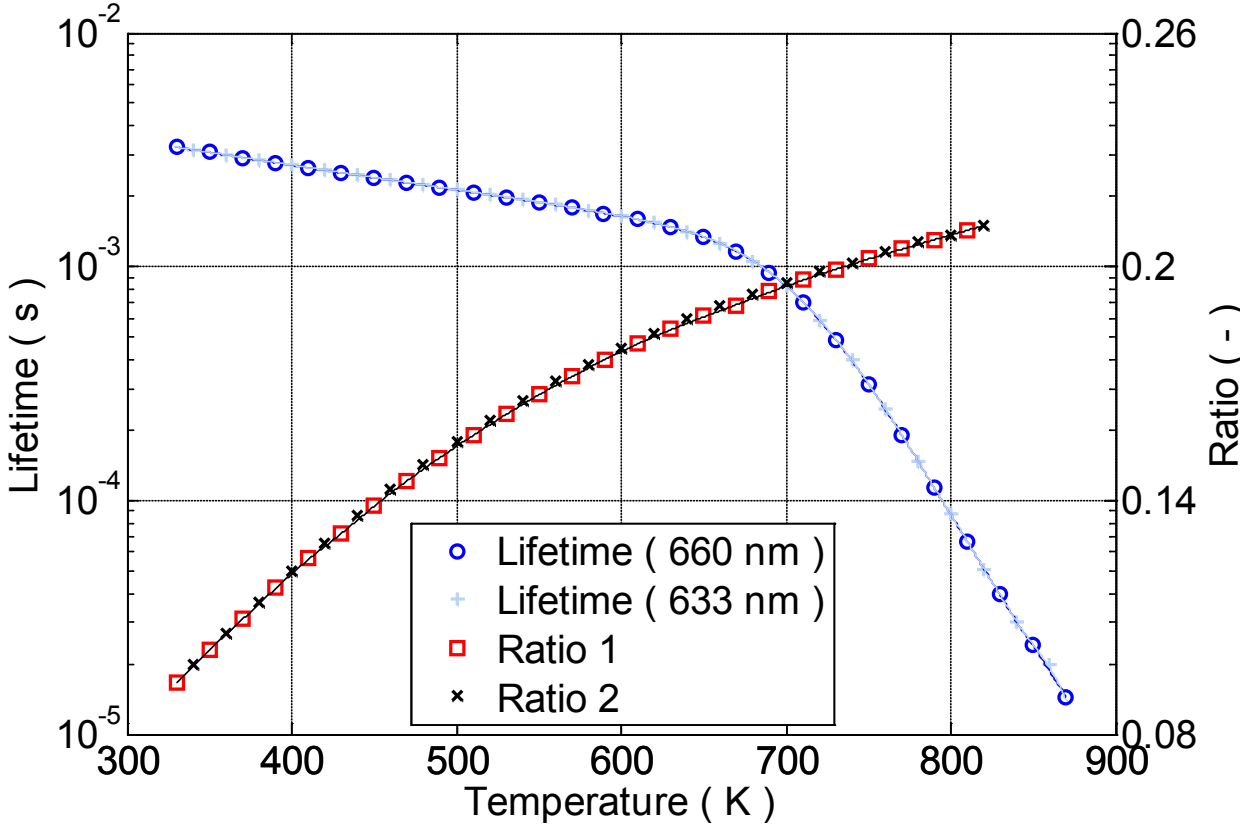
- Temperature-Lifetime / Temperature-Ratio characteristics



- Temperature-Lifetime characteristics of both spectral bands similar
- Temperature-Ratio characteristics for both ratios similar as well
- Very different sensitivities for lifetime approach and only slightly differing sensitivities for ratio approach

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Results: Precision I

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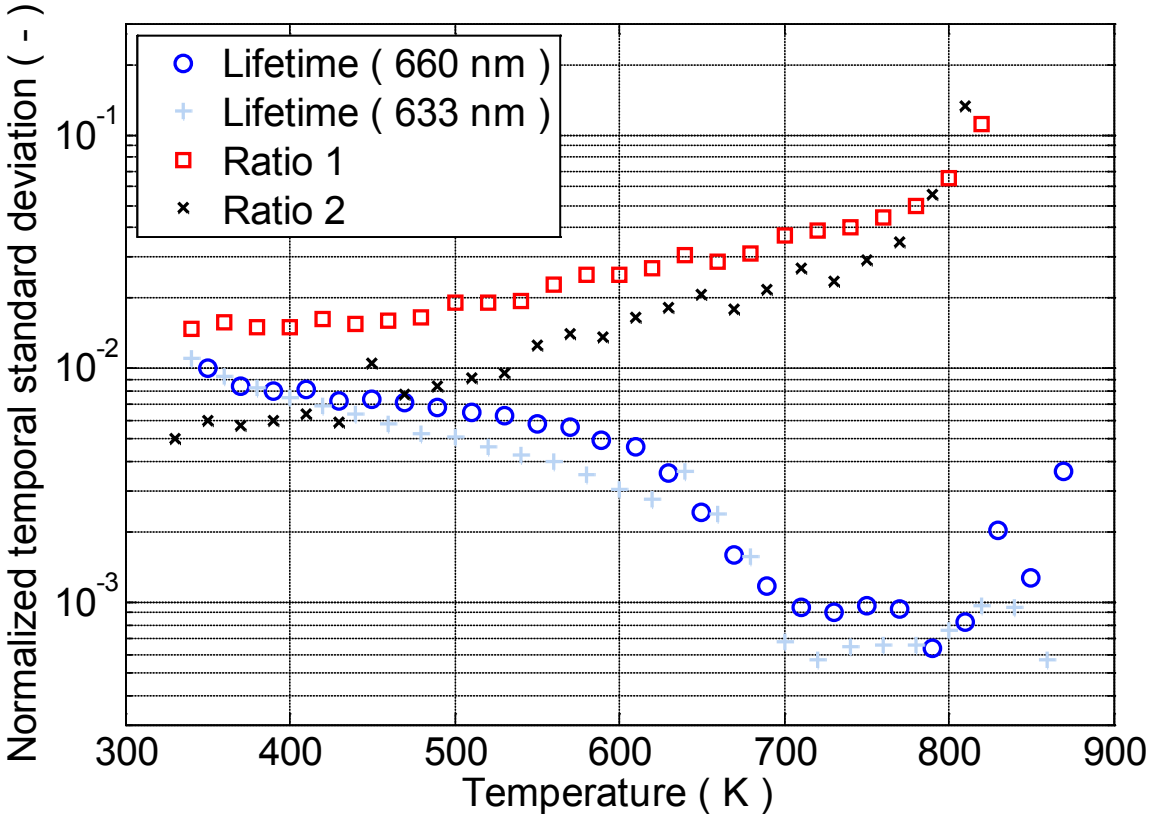
- Shot-to-Shot (**temporal**) standard deviations



- Comparable precision of both techniques at lower temperatures
- Lifetime method ~2 orders of magnitude better at higher temperatures

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Results: Precision II

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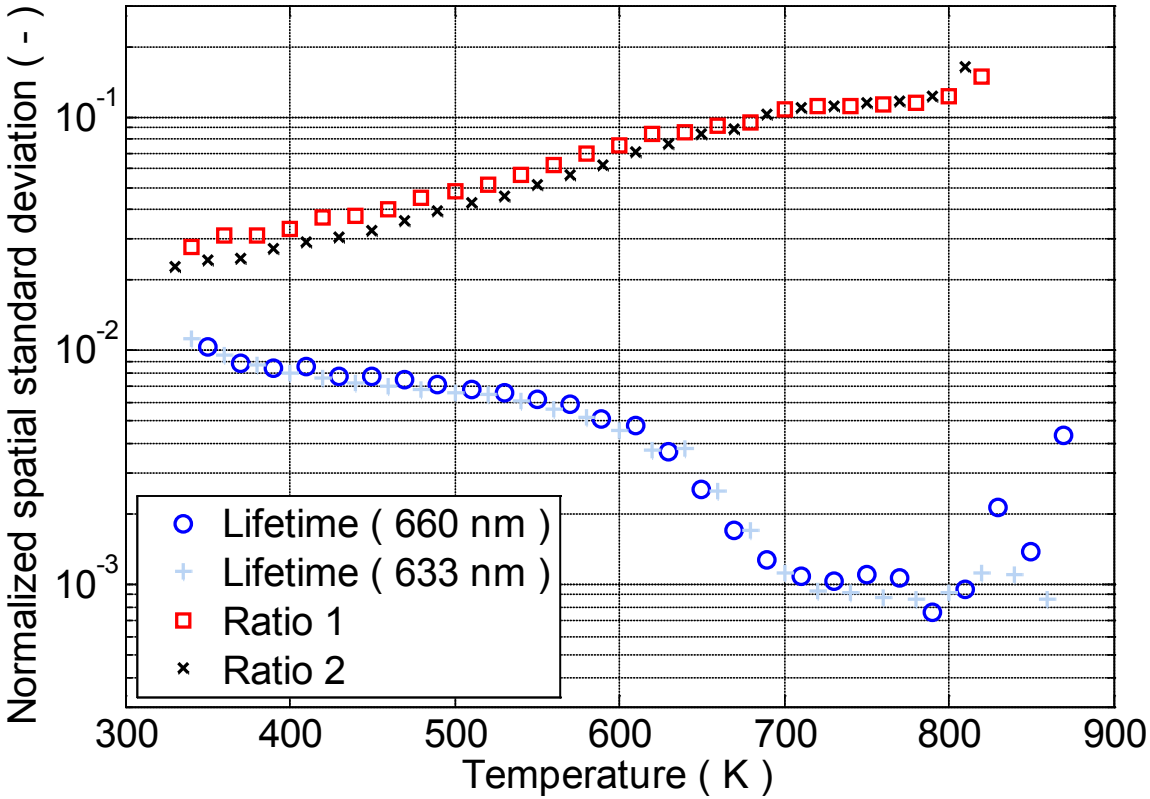
- Pixel-to-pixel (**spatial**) standard deviations



- Huge difference in spatial precision between the two techniques
- Spatial precision of lifetime method superior over the entire temperature range

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Results: Accuracy I

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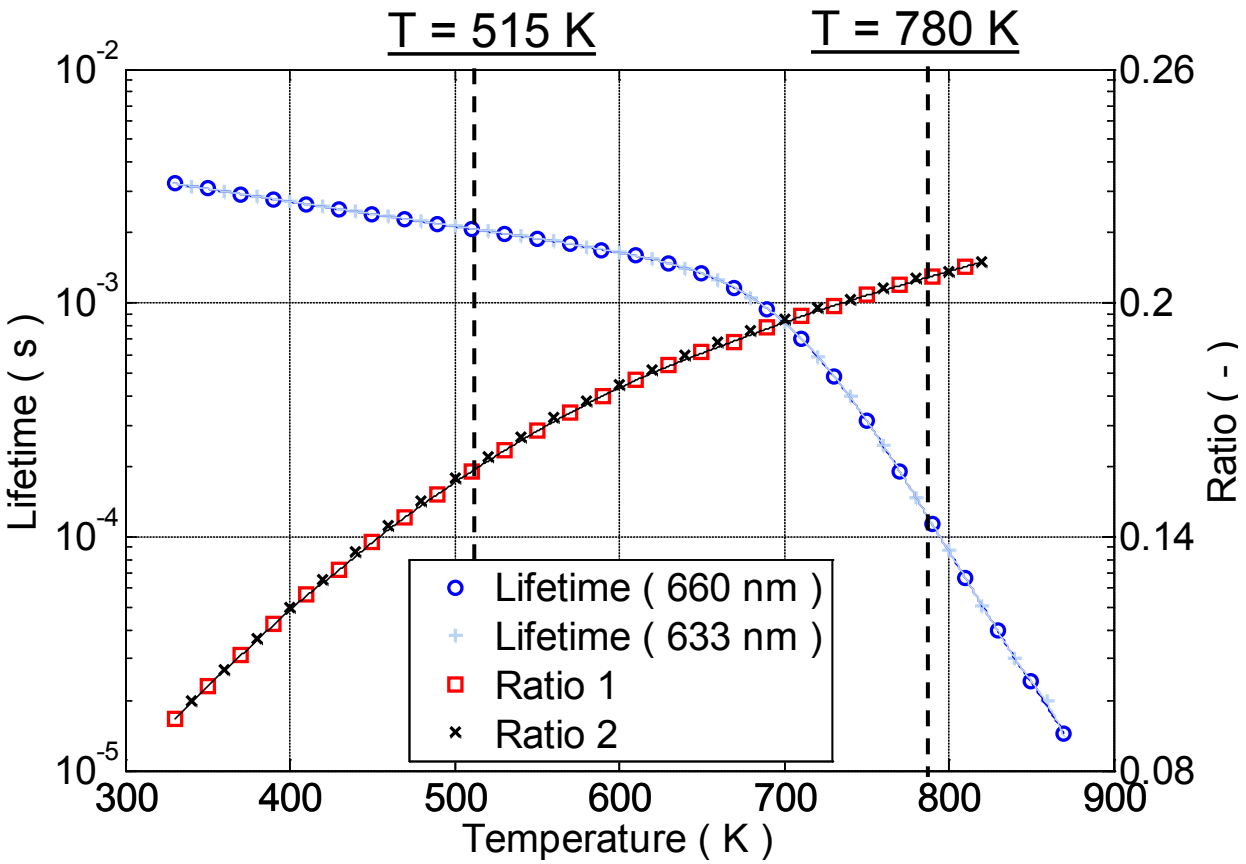
- Evaluation of systematic errors



- Evaluated at two different temperatures corresponding to two different sensitivities in the temperature lifetime characteristic
- Calibration at fixed conditions and then parametric variation:
  - Energy variation
  - Changing settings in optical setup

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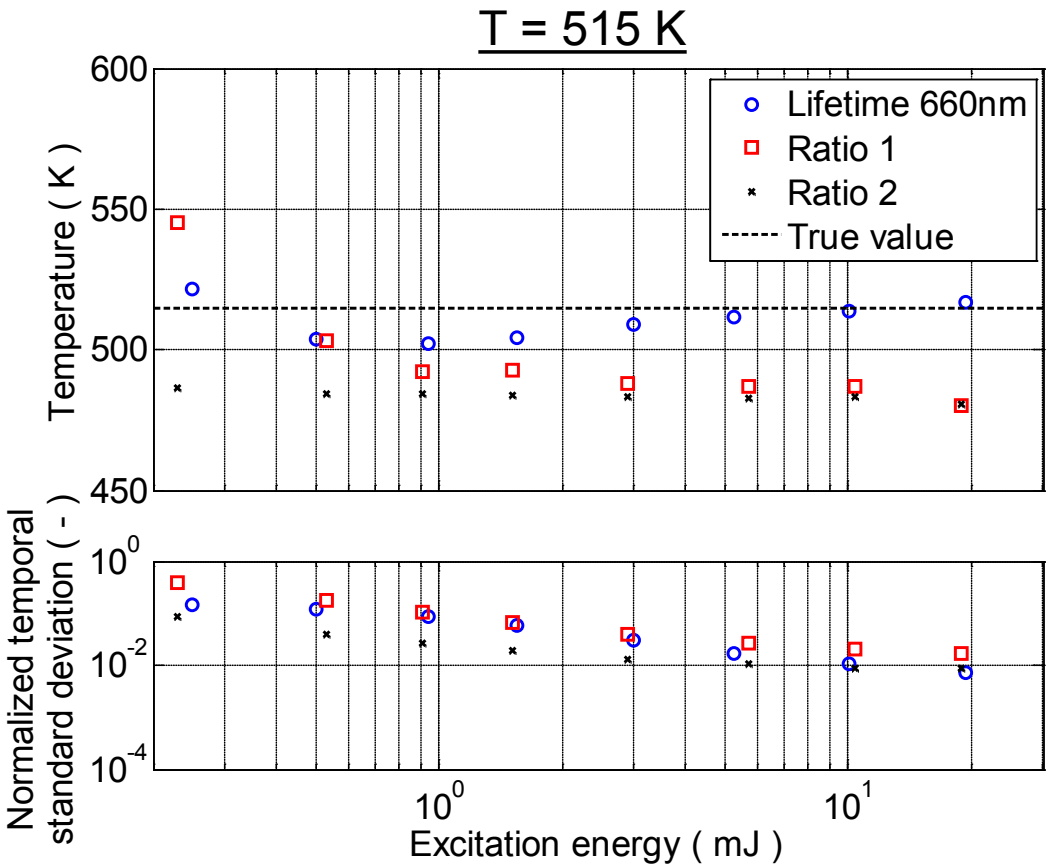
Results: Accuracy II

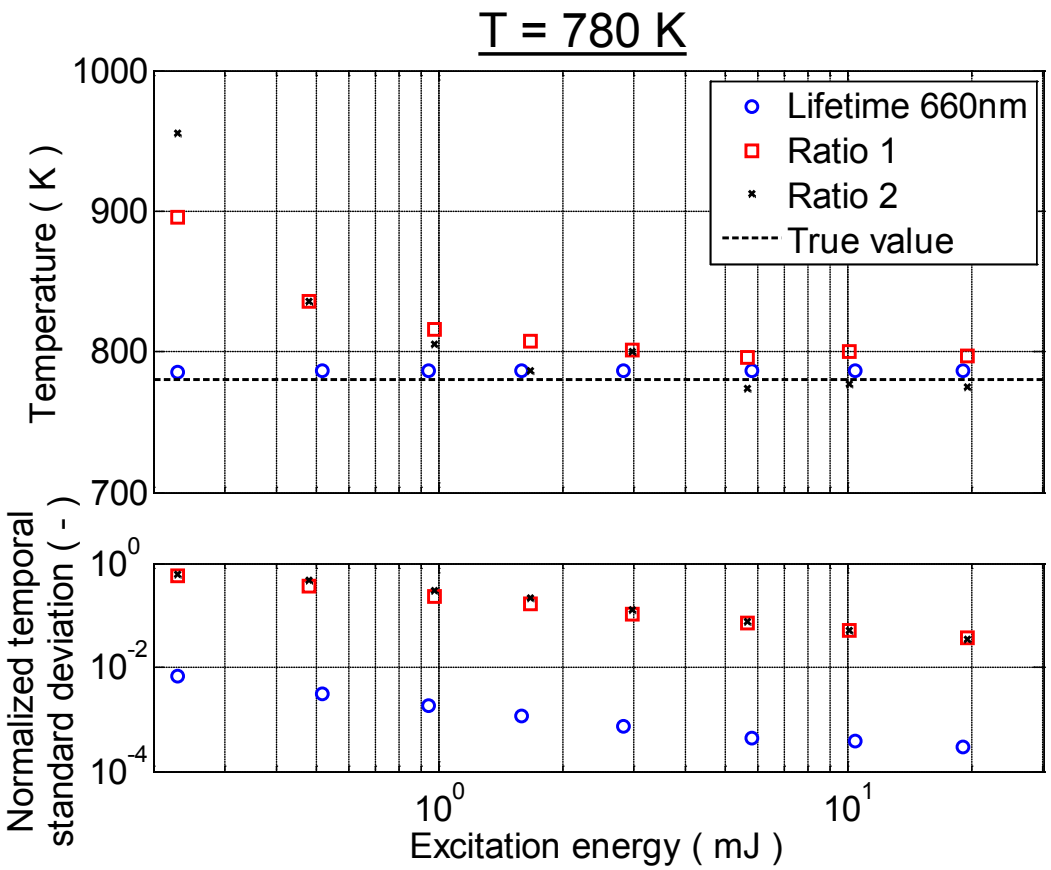
- Dependency on excitation energy at T = 515K



- Inaccuracy for too low excitations energies of lifetime approach well known (i.e. Brübach et al. 2008)
- Ratio 2 rather robust against energy variations, but inaccuracy over whole energy range

Results: Accuracy III

- Dependency on excitation energy at T = 780K



- Lifetime approach very accurate due to high sensitivity
- Ratio 1 & 2 show overestimation of more than 100 K at lower energies

Results: Accuracy IV

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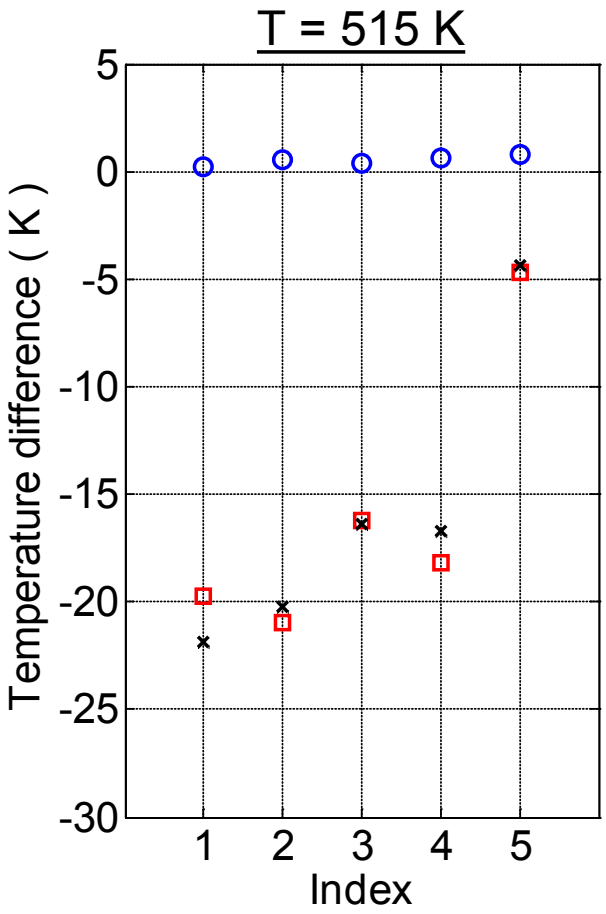
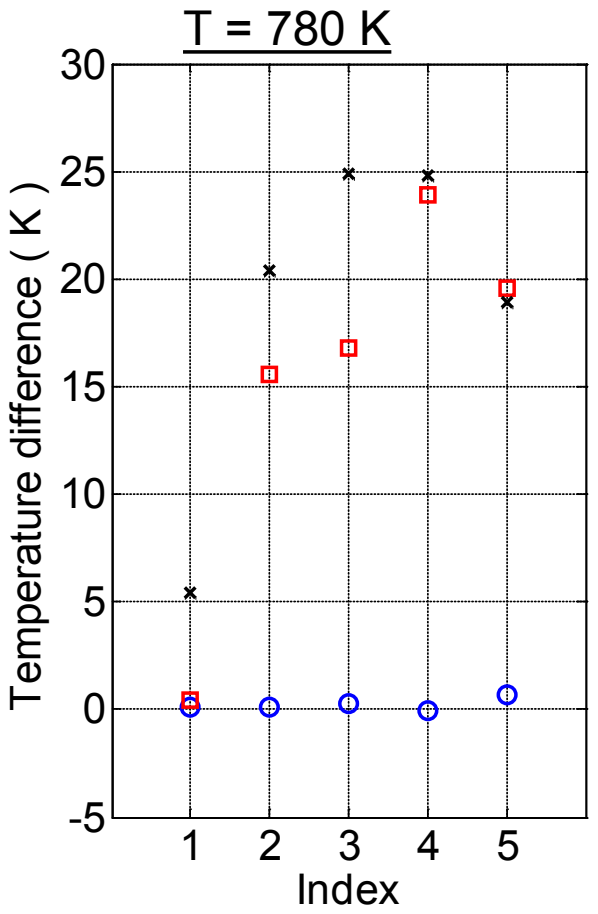
- Accuracy due to changes of settings in the optical setup



Lifetime (660 nm)
Ratio 1
Ratio 2

Index
1 – Filter rotation
2 – Increase distance (1cm)
3 – Increase distance (2cm)
4 – Increase distance (4cm)
5 – Change camera angle



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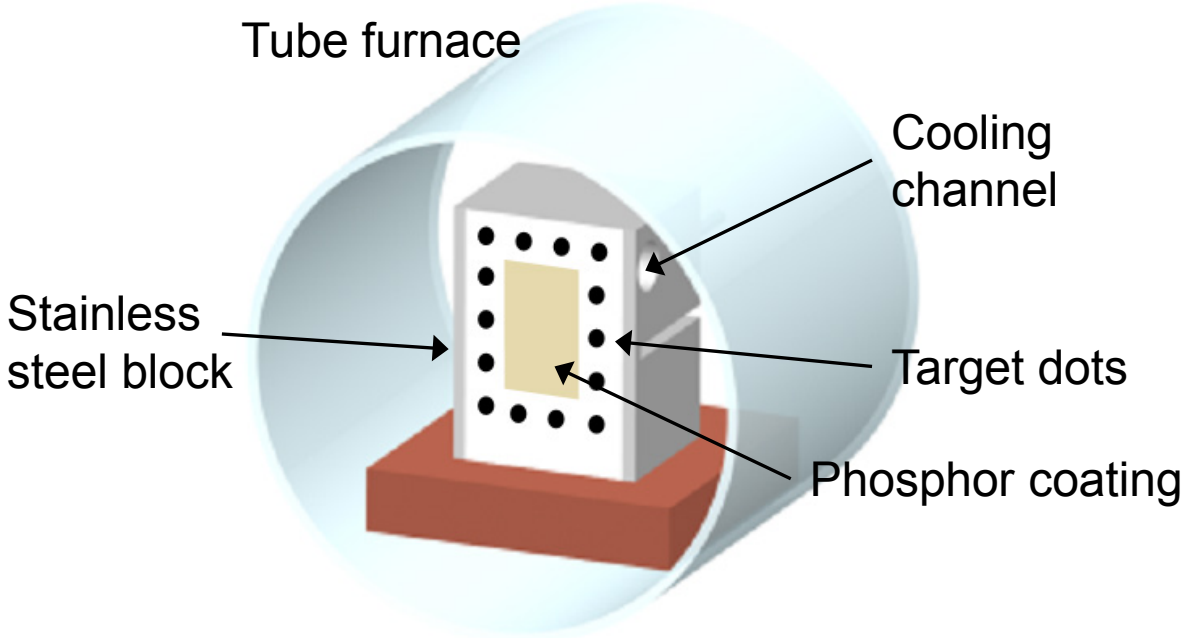
Results: Cooling device I

- Stainless steel block with cooling channel placed inside oven
- When block is at designated temperature, cold water is pumped through cooling channel
- For image mapping purposes target dots have been transferred to device



Kissel, T., PhD Thesis, TU Darmstadt, 2011

Results: Cooling device II

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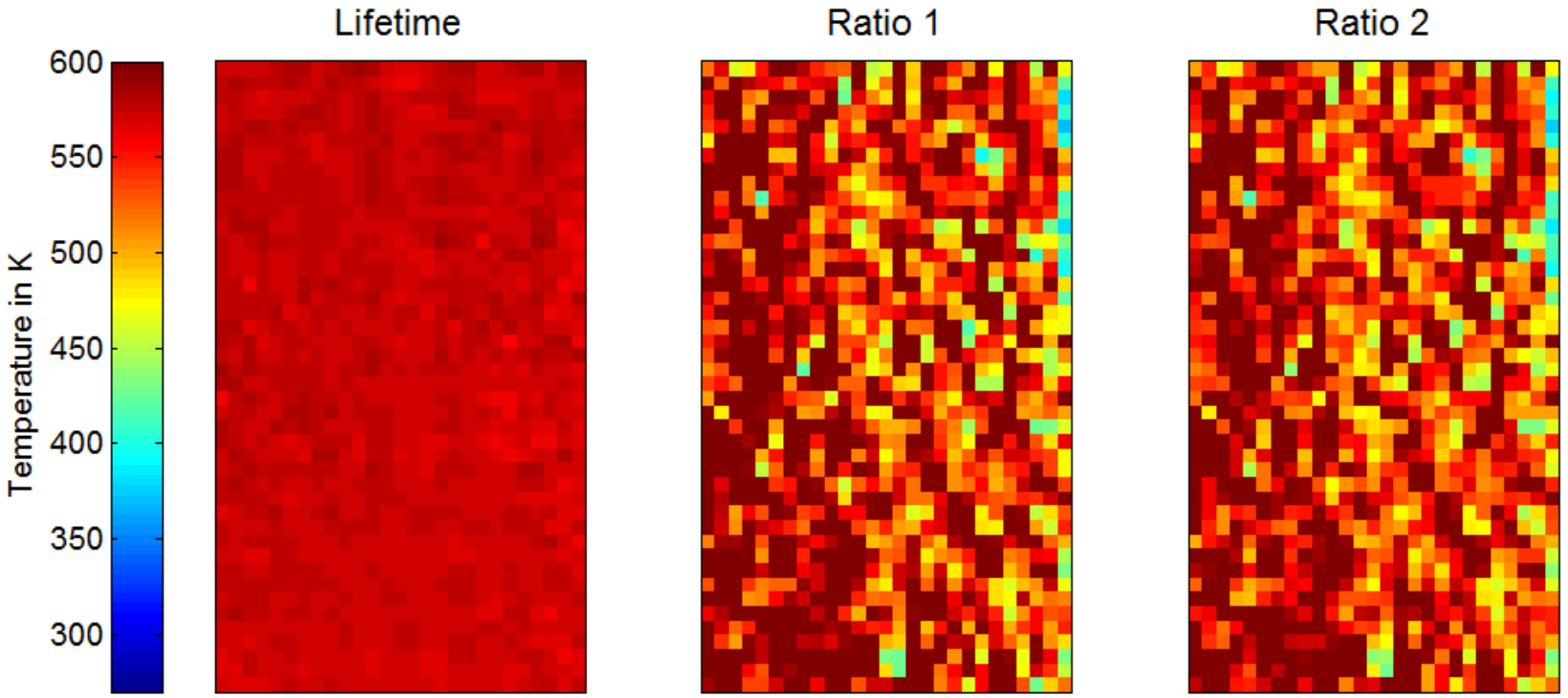
- Transient Experiment
- Same set of data for all three methods



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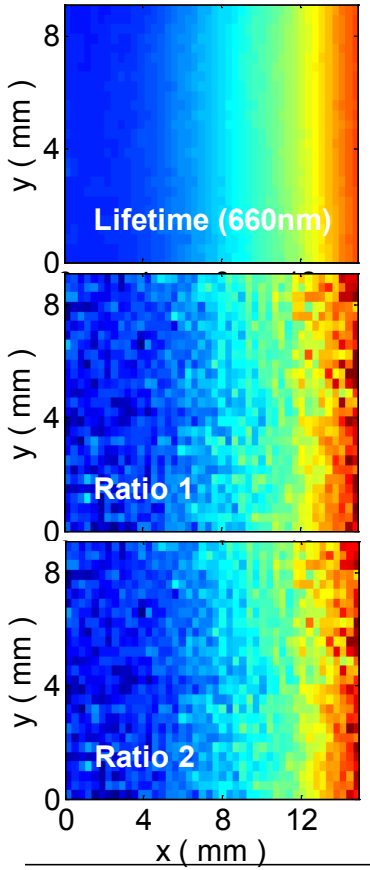
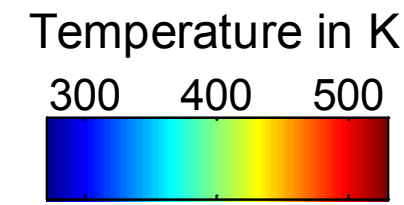
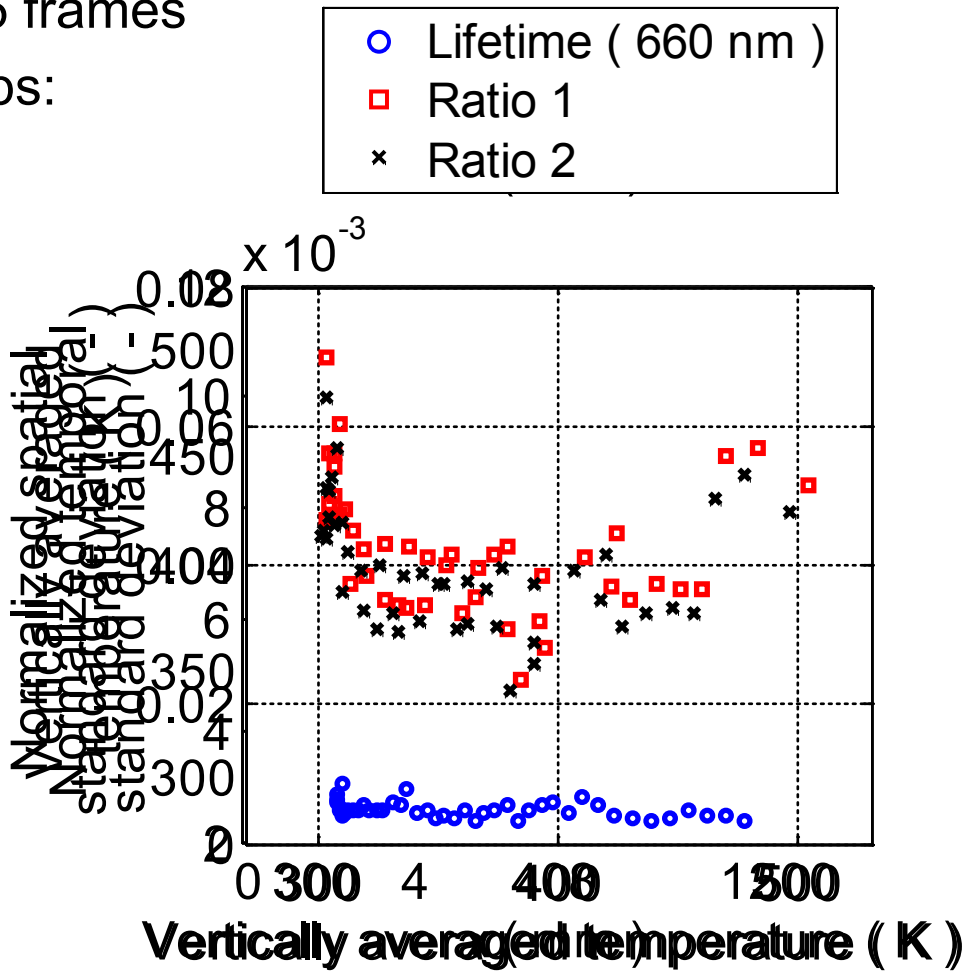
Results: Cooling device III

- Stationary T-distribution over last 16 frames
- Statistics for these temperature maps:





Vertical binning



Summary & Conclusions

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Comparison of Mg_4FGeO_6: Mn for the lifetime and the intensity ratio method in terms of

- Precision
- Accuracy
- Application (cooling device)

Main results

- High temperature range (>650K): Lifetime method is superior in all aspects
- Low temperature range: Lifetime method superior for spatial standard deviation and for accuracy, similar temporal standard deviations
- Only valid for the phosphor under consideration
- For other phosphors similar investigations required

Fuhrmann PCI 34, 2013, Fuhrmann et al.

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Error treatment for the decay-time method

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1. Introduction
2. Measurement chain / Error sources
3. Applications
4. Summary

For details see PECS 2013, Brübach et al.

1. Introduction

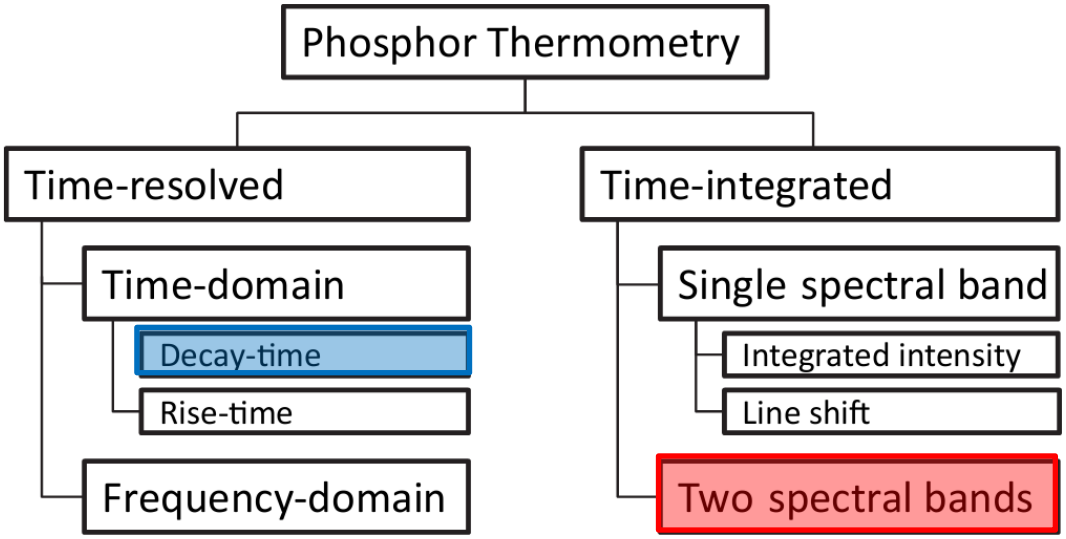
2. Measurement chain / Error sources

3. Applications

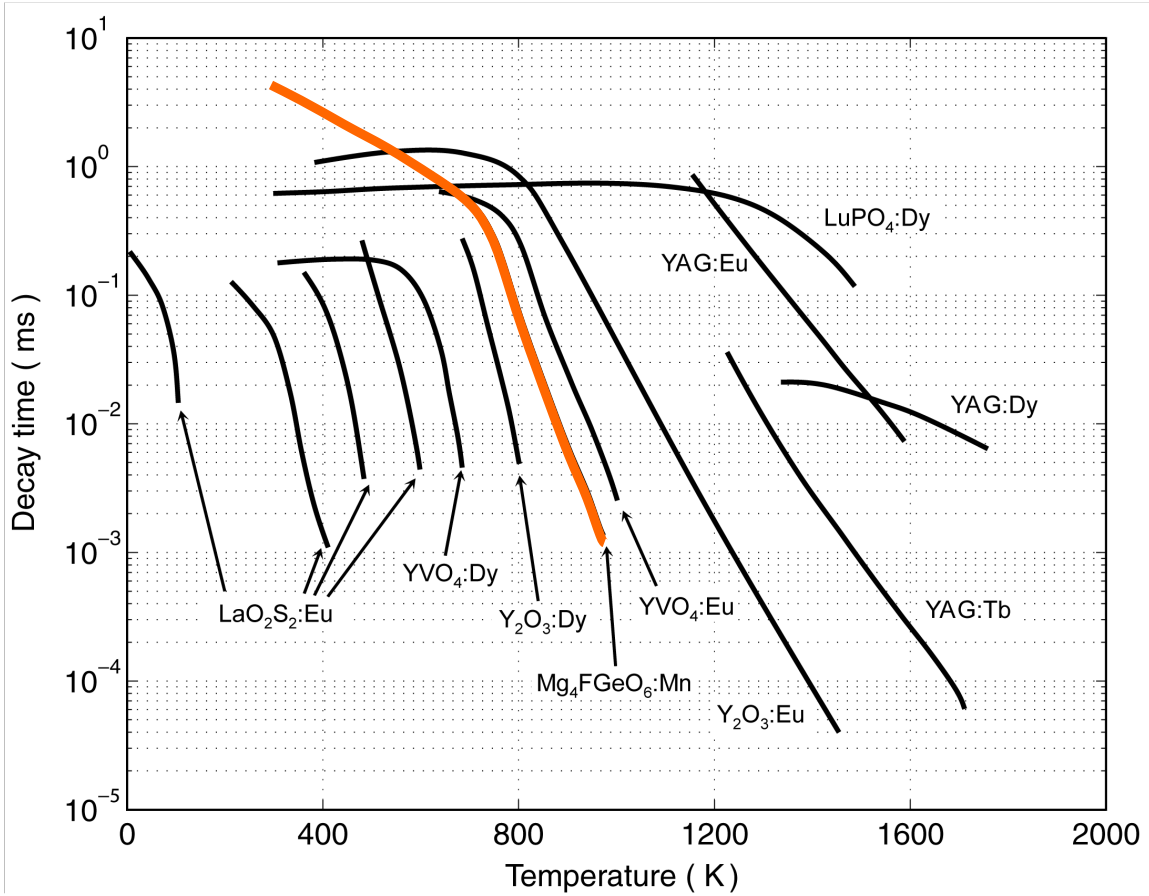
4. Summary

Combustion applications: mostly used approaches

- Most often used approaches are decay-time and two-spectral-band-method
- As discussed: Decay-time method does have the potential for superior precision and accuracy (especially in 2D application); see Fuhrmann, Brübach and Dreizler, PCI 33, 2013
- Decay-time varies with temperature due to varying energy transfer processes



Thermographic Phosphors: materials showing temperature dependent decay times



Approx. 100 different phosphors documented in literature
See Brübach et al. PECS 2013

Magnesium-Fluorogermanate doped with manganese:

Mg_4FGeO_6:Mn

Allison and Gillies, Rev. Sci. Instr., 68:2615-2650, 1997.

Spectra

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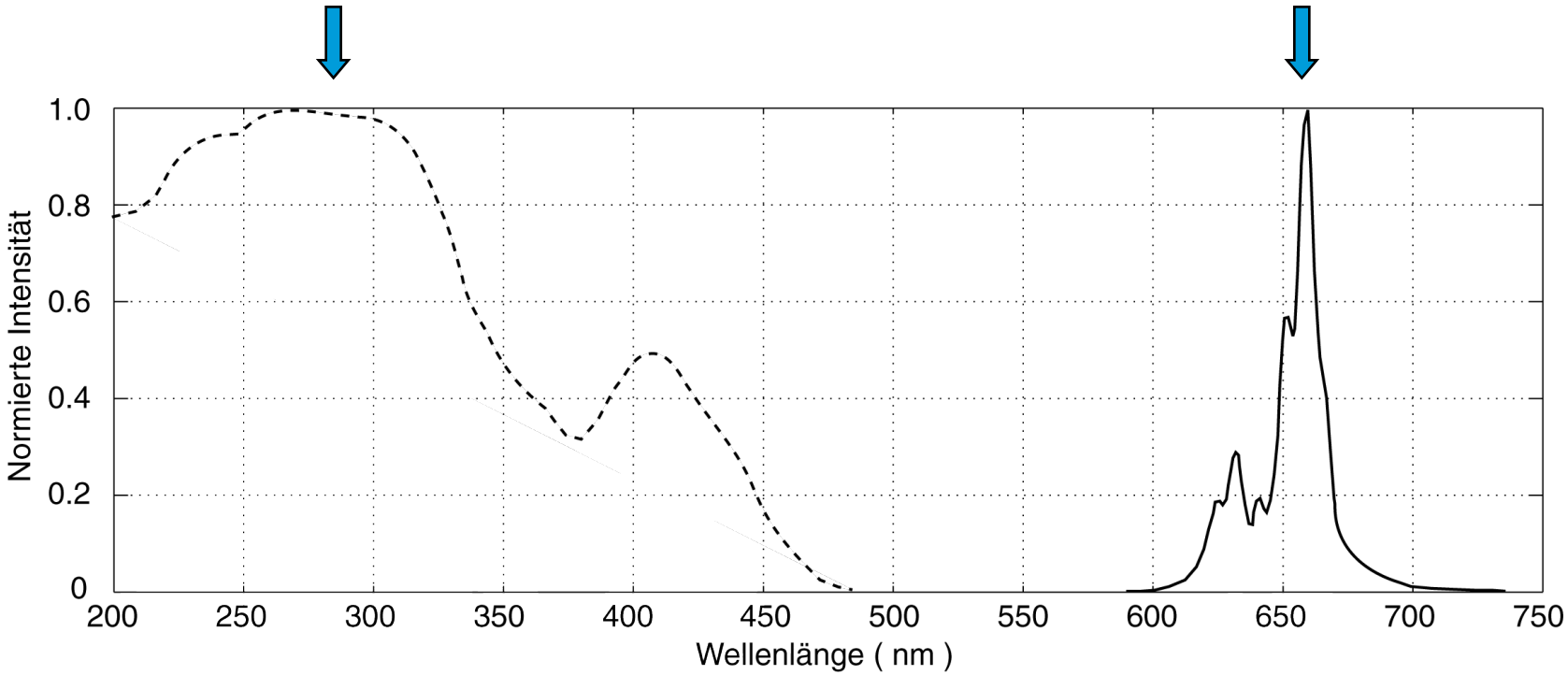
$Mg_4FGeO_6:Mn$

Excitation

Possible by standard laser wavelength

Emission

may interfere with luminous combustion



Experimental Setup – 0D

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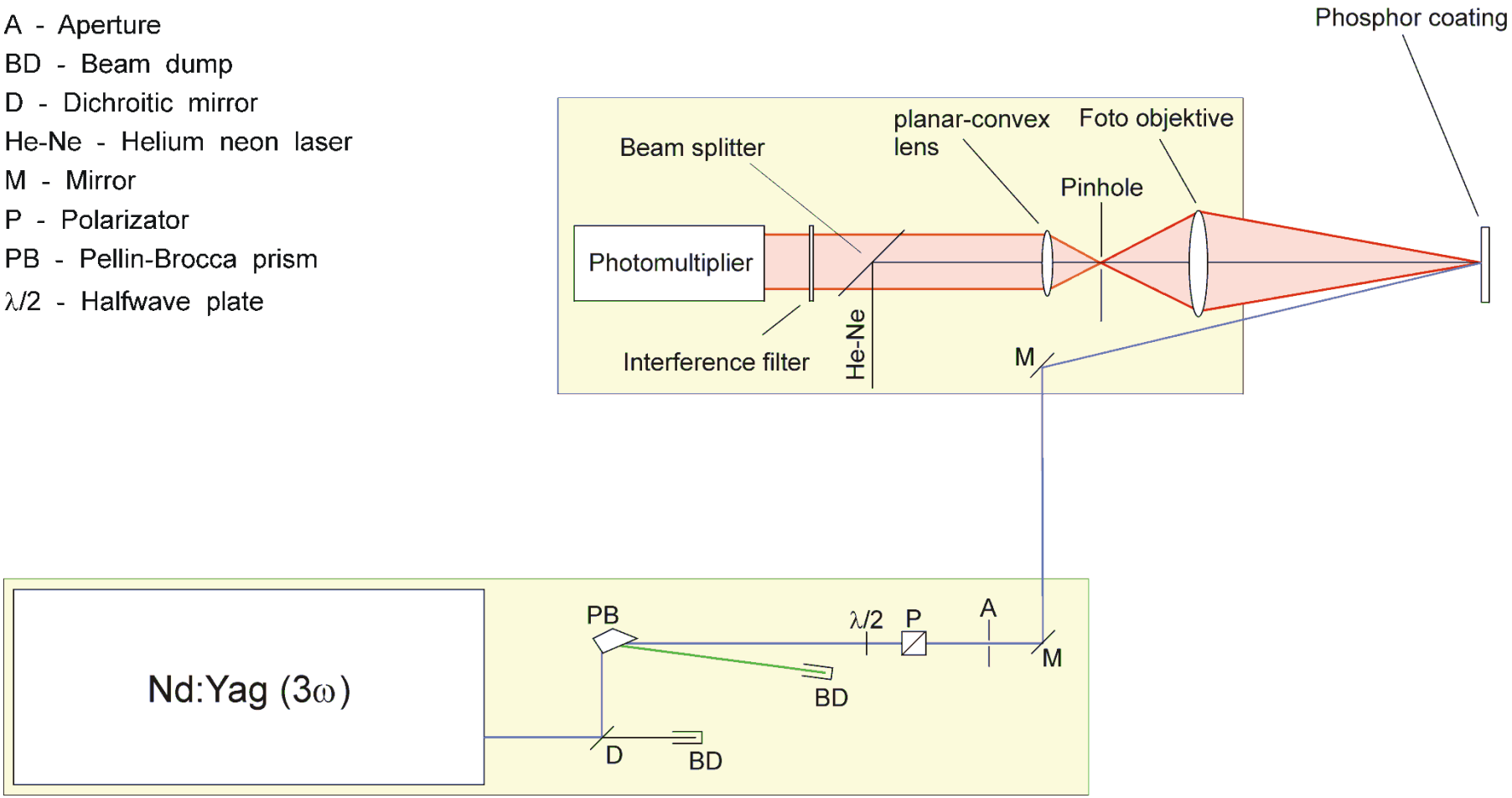
A - Aperture
BD - Beam dump
D - Dichroitic mirror
He-Ne - Helium neon laser
M - Mirror
P - Polarizator
PB - Pellin-Brocca prism
λ/2 - Halfwave plate



Experimental Setup – 2D

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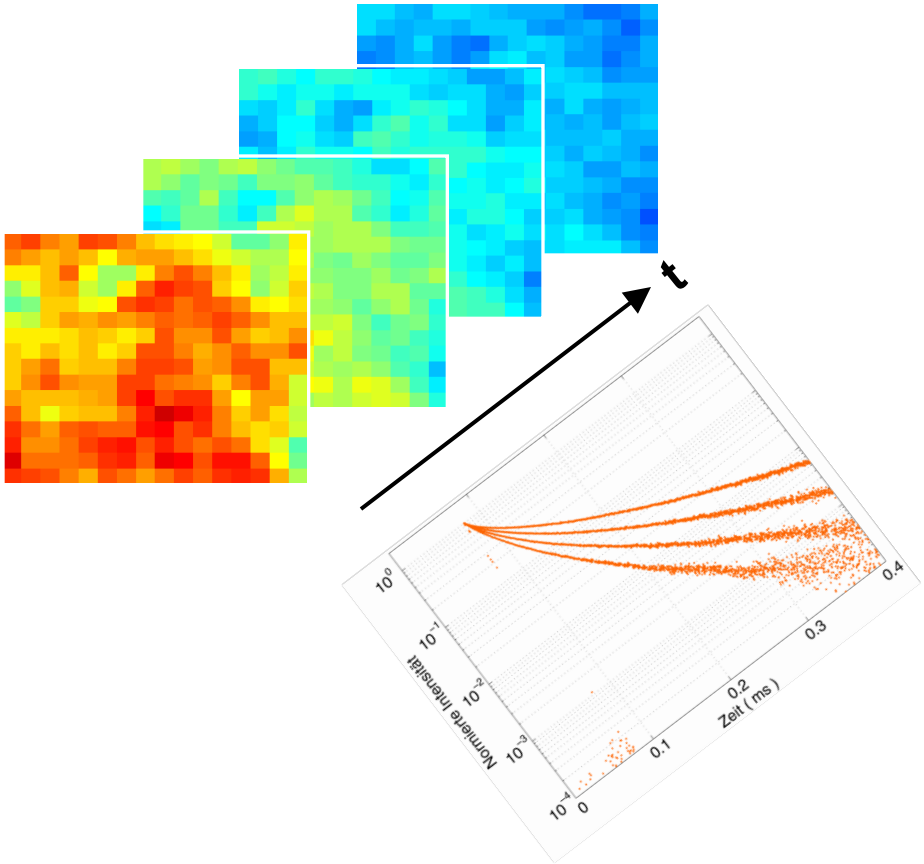
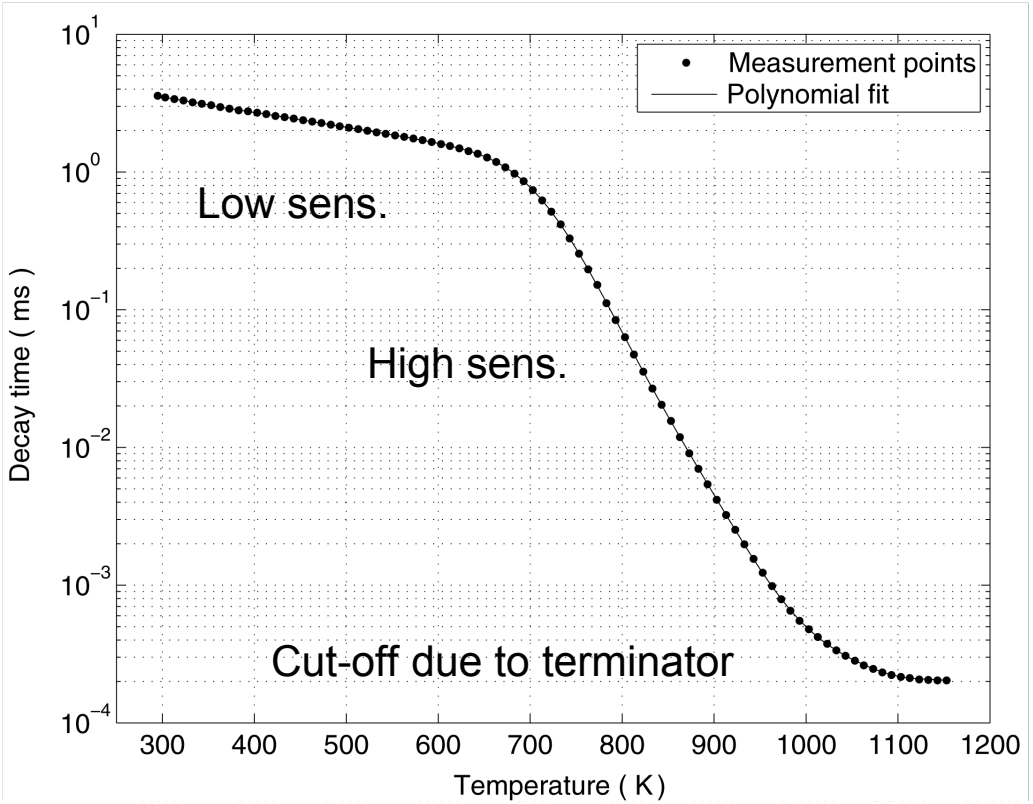
CMOS Kamera LaVision HSS6:

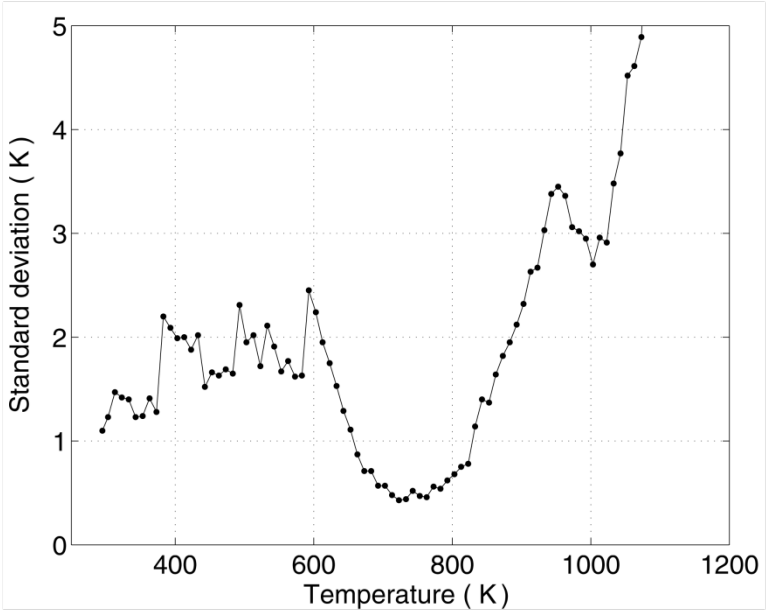
- Dynamic Range: 12 bit
- max. frame rate of 675 kHz at a resolution of 64 x 16 Pixels



Calibration in well-controlled environments (oven)



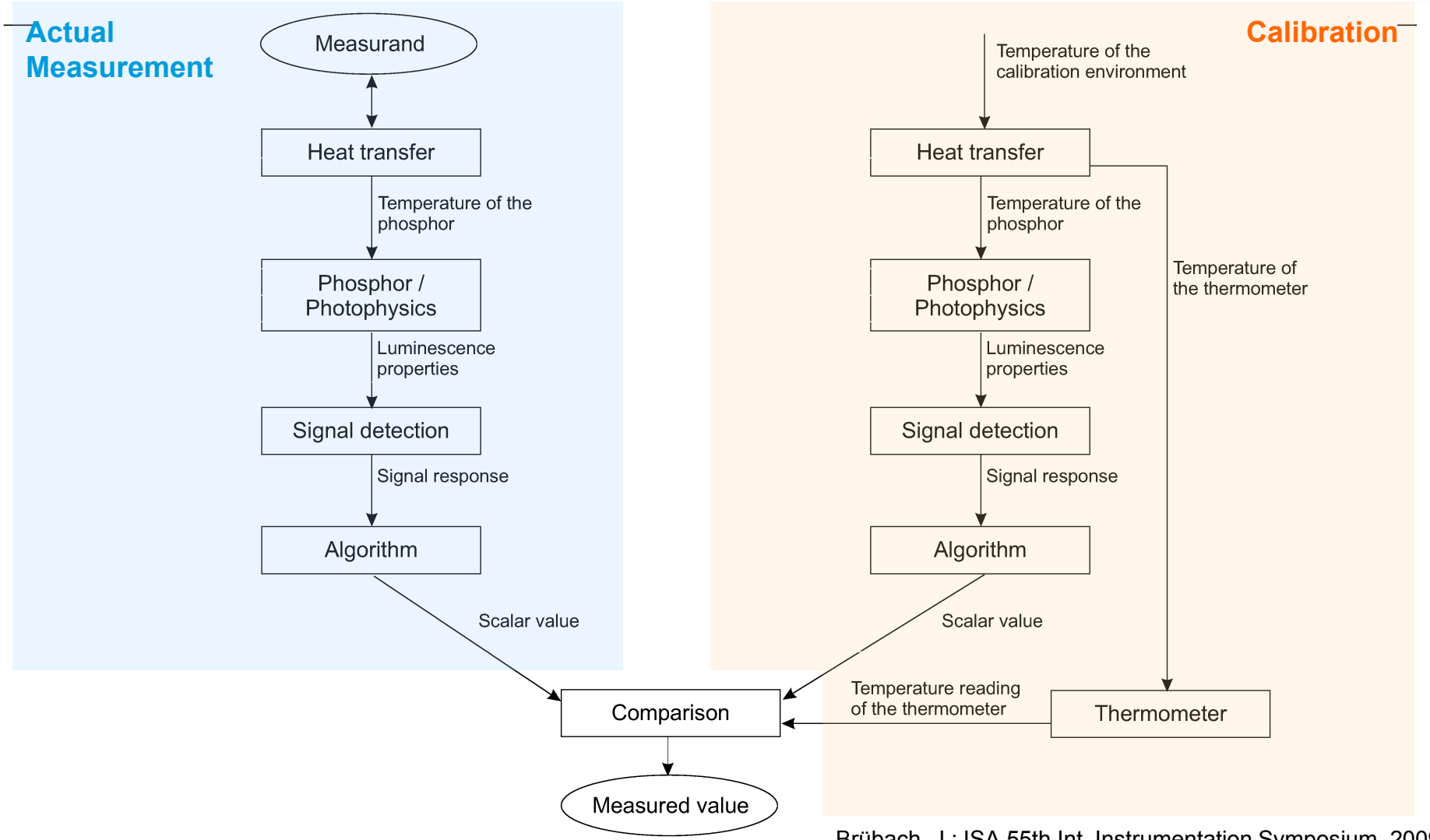
- Phosphor: Mg_4FGeO_6:Mn
- Substrate: Stainless Steel (1.4301)
- Gas phase pressure: 1 bar (air)
- Detection: PMT at 500 Ω



TECHNISCHE UNIVERSITÄT DARMSTADT

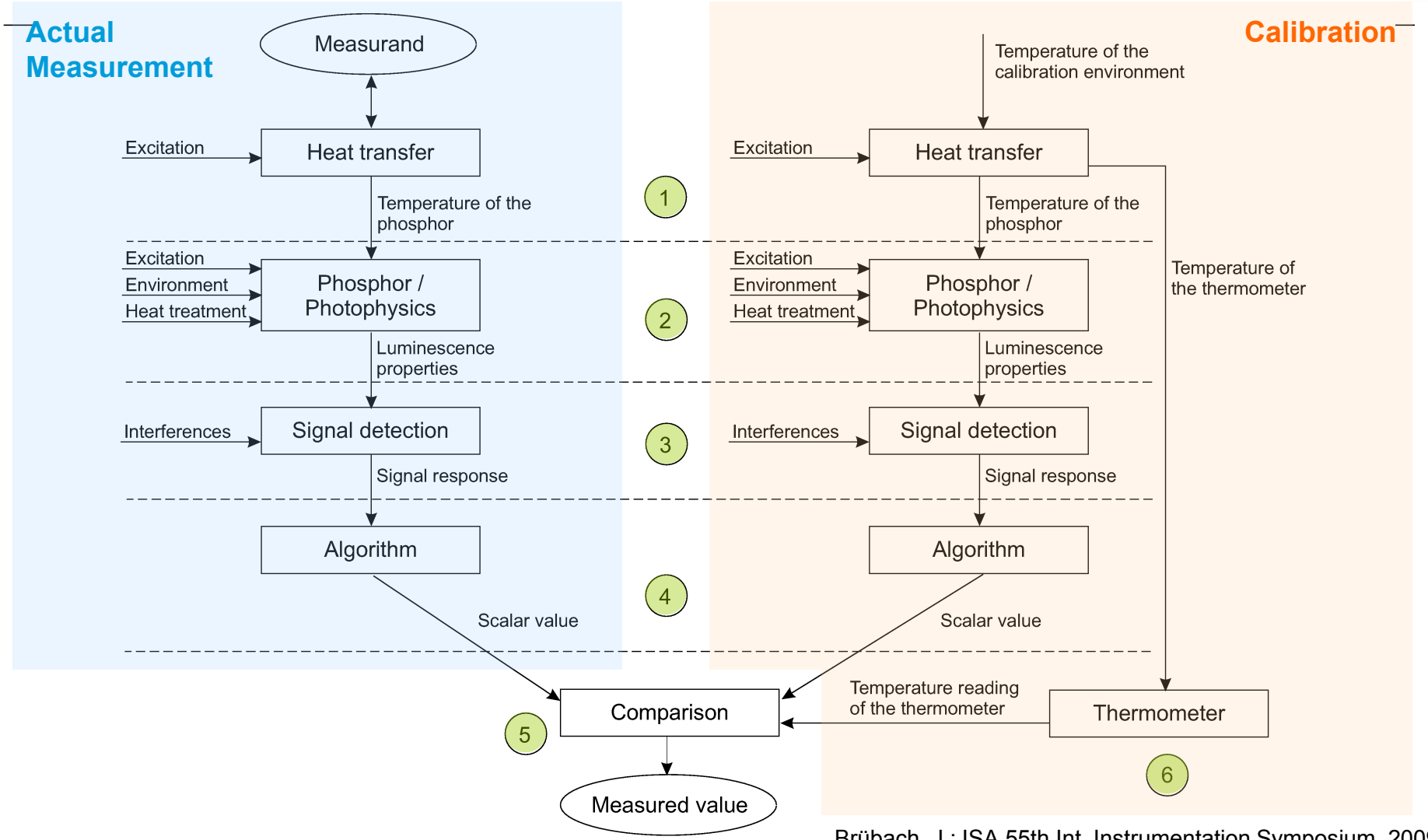
1. Introduction
2. Measurement chain / Error sources
3. Applications
4. Summary

Measurement chain



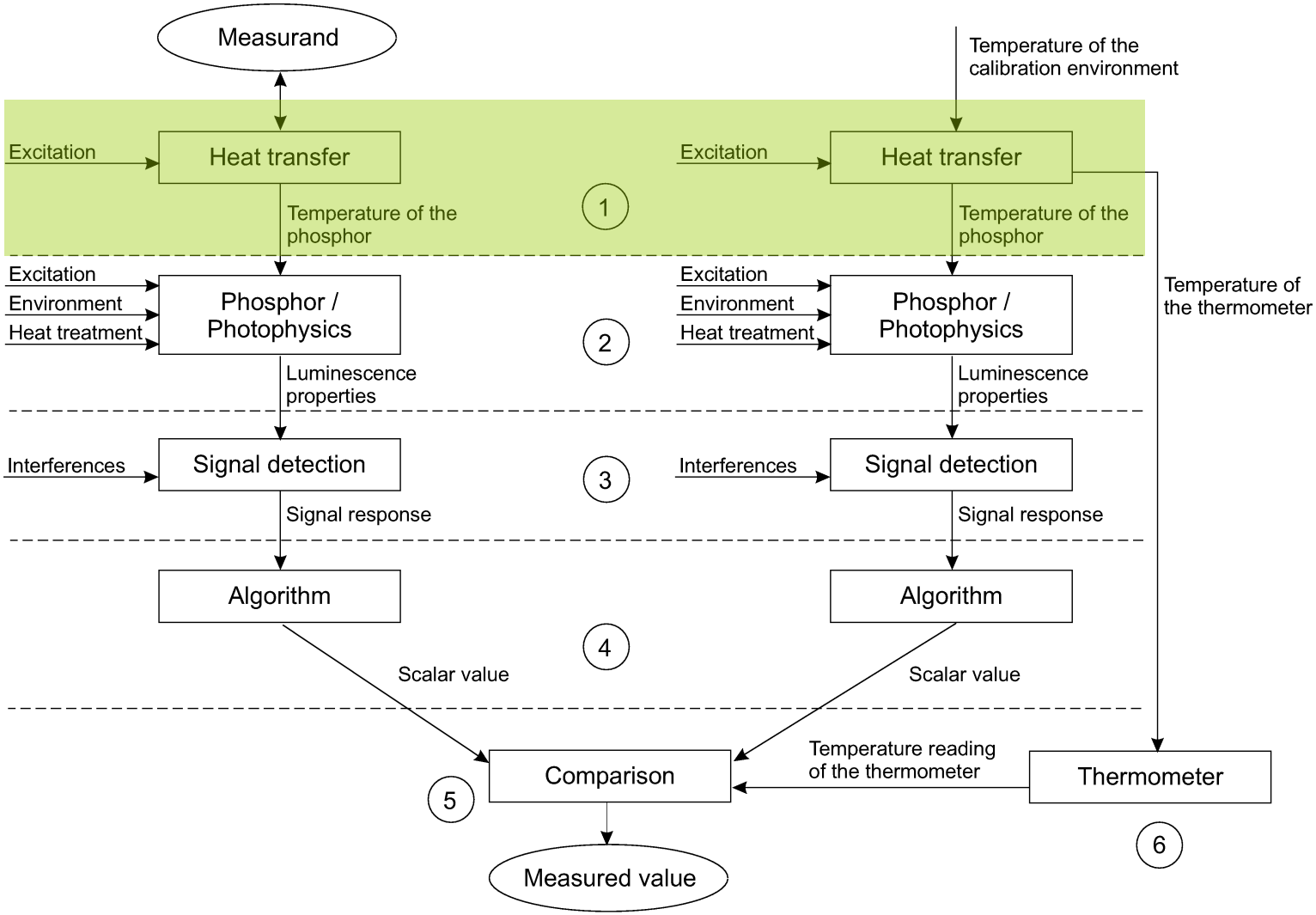
Brübach, J.; ISA 55th Int. Instrumentation Symposium, 2009

Measurement chain



Brübach, J.; ISA 55th Int. Instrumentation Symposium, 2009

Error class 1:
Thermal interactions



Error class 1:
Thermal interactions

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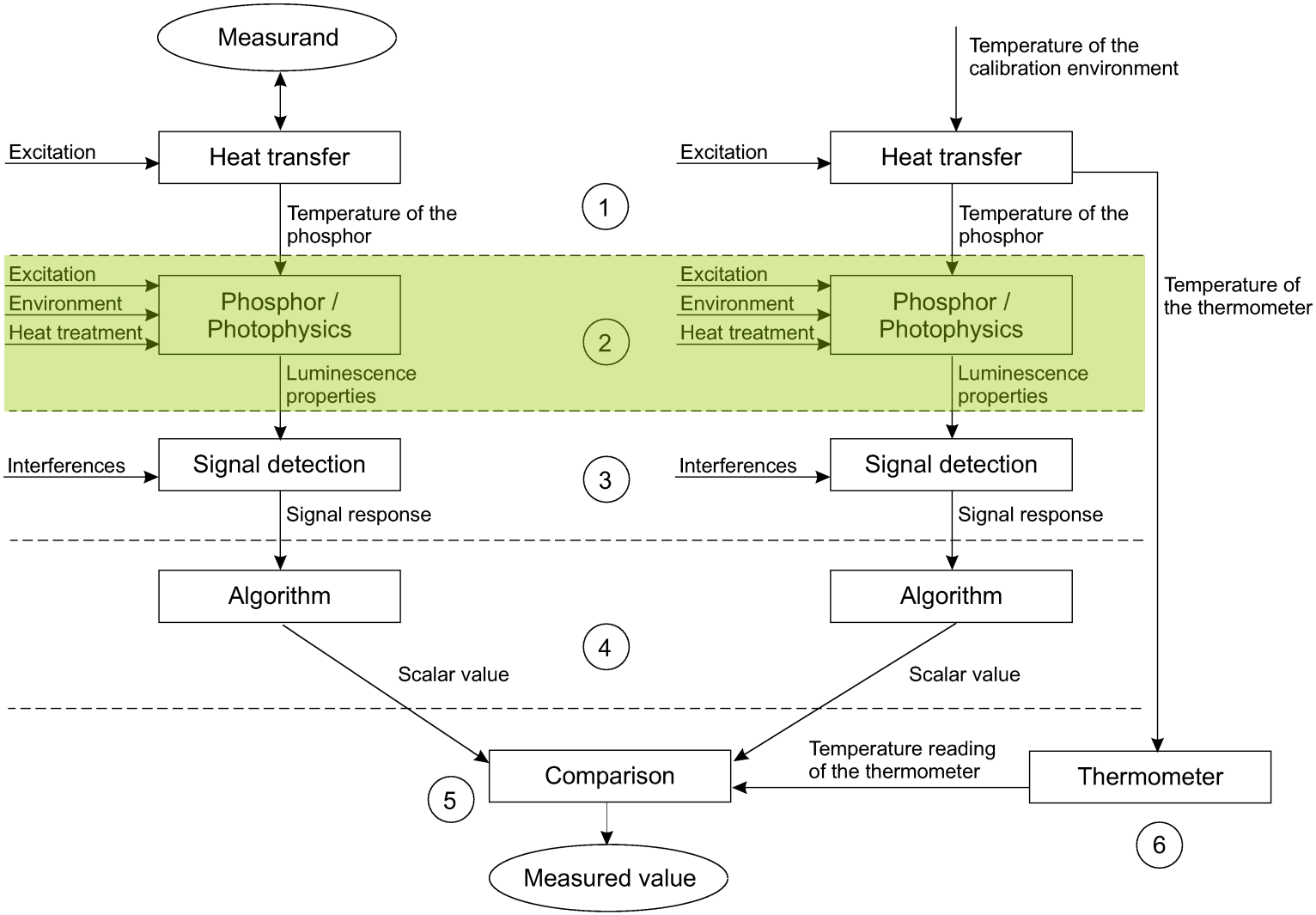
- Device under test (DUT) and phosphor or phosphor and calibration thermometer are not in thermal equilibrium
- Impact of the presence of the phosphor on the thermal state of the DUT (e.g. heat insulation) → “semi-invasive” method
- Excitation induced heating of the phosphor → check by power scan

Error class 2:
Photophysical properties of the phosphor



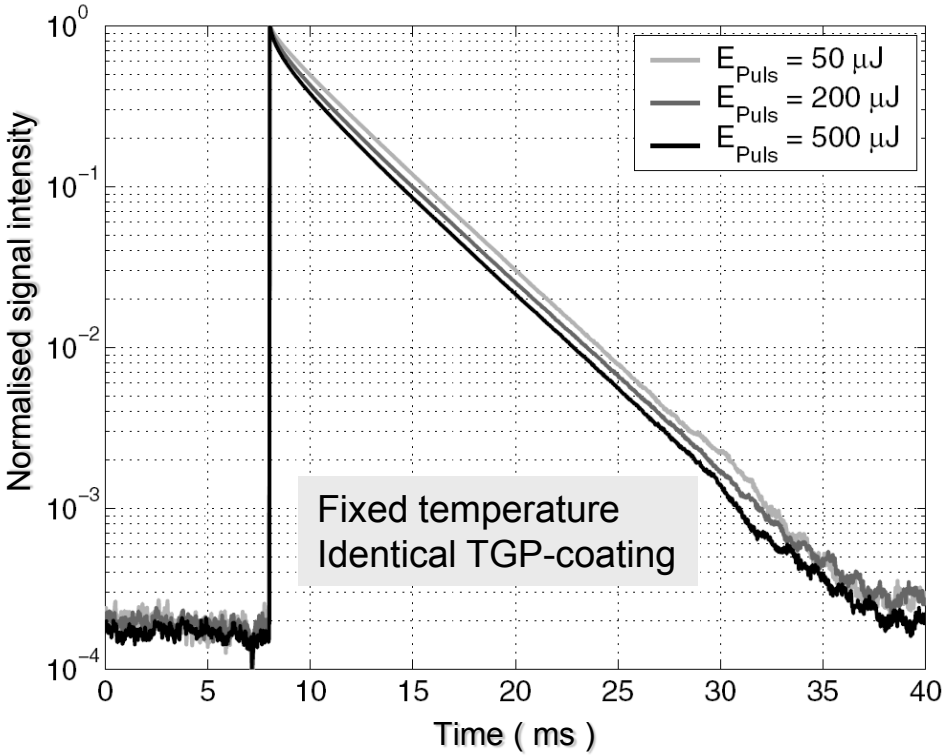
Error class 2:
Photophysical properties of the phosphor

TECHNISCHE UNIVERSITÄT DARMSTADT

- Impact of the transfer function of the phosphor
  - ➔ Temperature sensitivity, varies with temperature
  - ➔ Temporal low pass character due to finite decay time (thermal inertia versus decy time)

- Parameters that manipulate the transfer function of the phosphor
  - ➔ Diffusion processes between the phosphor material and the substrate due to heat treatments
  - ➔ Chemical and physical environment (oxygen quenching)
  - ➔ Laser excitation (variations with intensity)

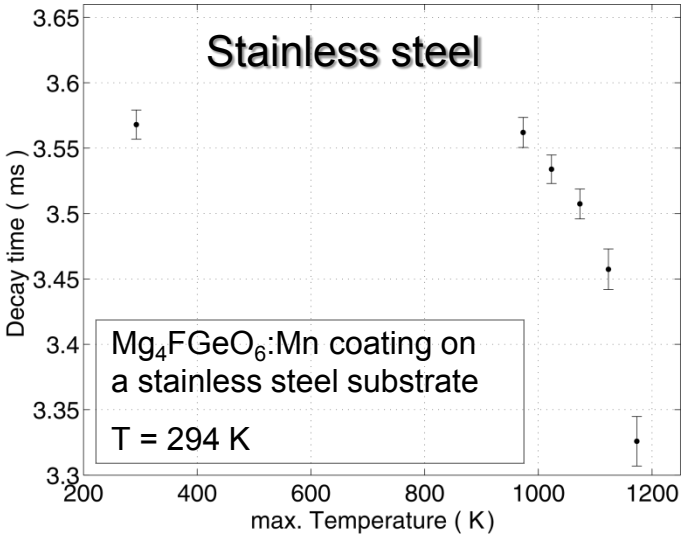
Error class 2:
Excitation irradiance

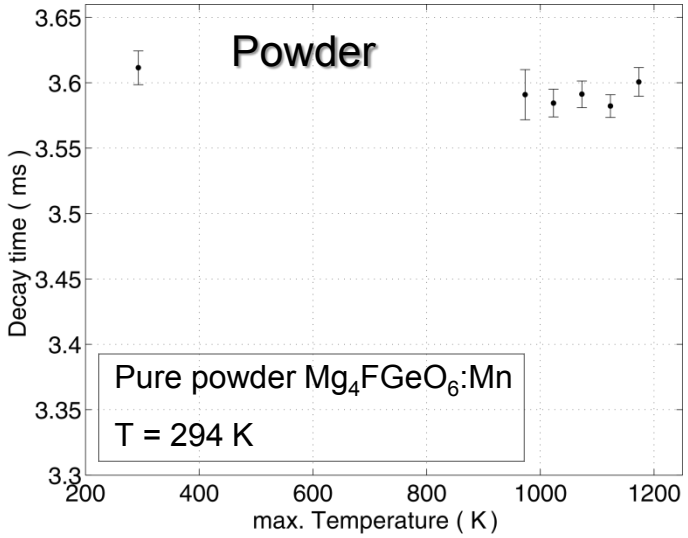


- Decay behaviour “more multi-exponential” at higher laser intensities
- Significant influence of the position of the fitting window

Brübach, J.; Feist, J. P.; Dreizler, A.: Meas. Sci. Technol., 19(2):025602, 2008.

Error class 2:
Decay time @ 294 K after heat treatment



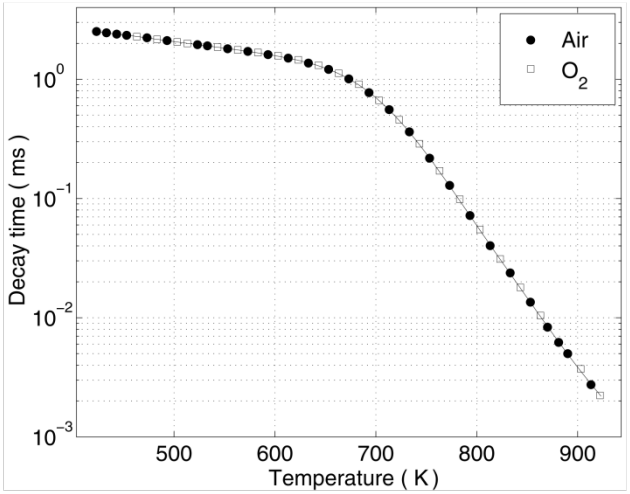


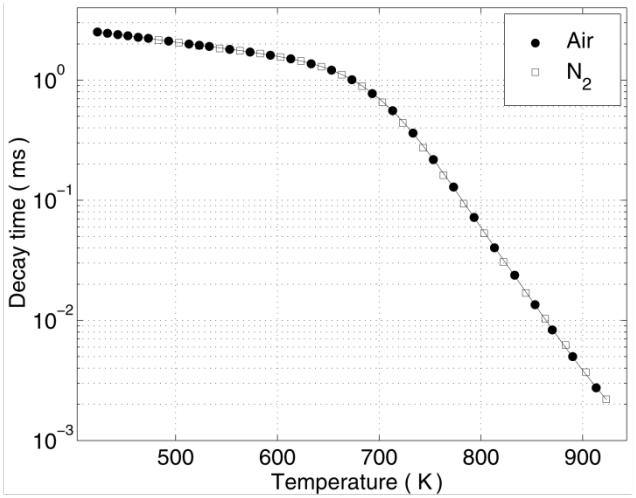
➡ Dependency on:
- Substrate material
- Duration of the heat treatment
- Heat treatment temperature

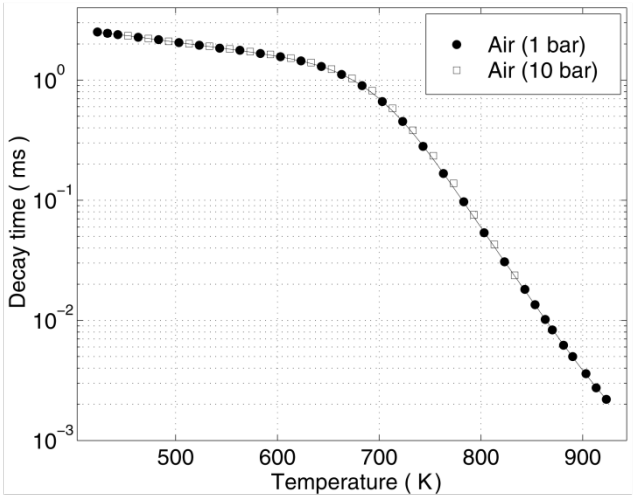
➡ Diffusion process between phosphor und substrate

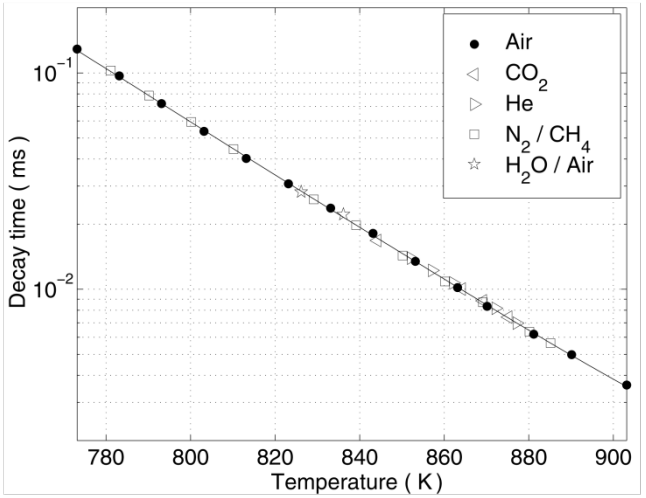
Brübach, J.; Feist, J. P.; Dreizler, A.: Meas. Sci. Technol., 19(2):025602, 2008.

Error class 2:
Surrounding gas phase







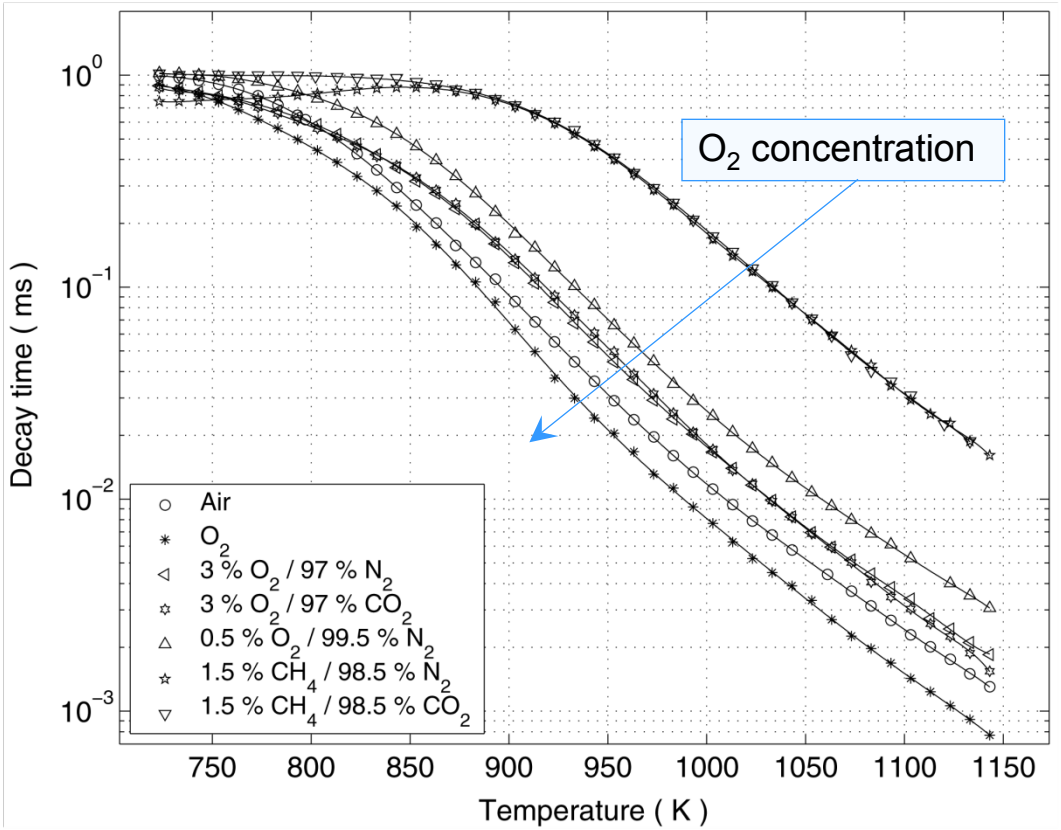


Mg_4FGeO_6:Mn

No significant dependency on the composition and pressure of the gas phase

Brübach, J.; Dreizler, A.; Janicka, J.: Meas. Sci. Technol., 18(3):764–770, 2007.

Error class 2:
Surrounding gas phase

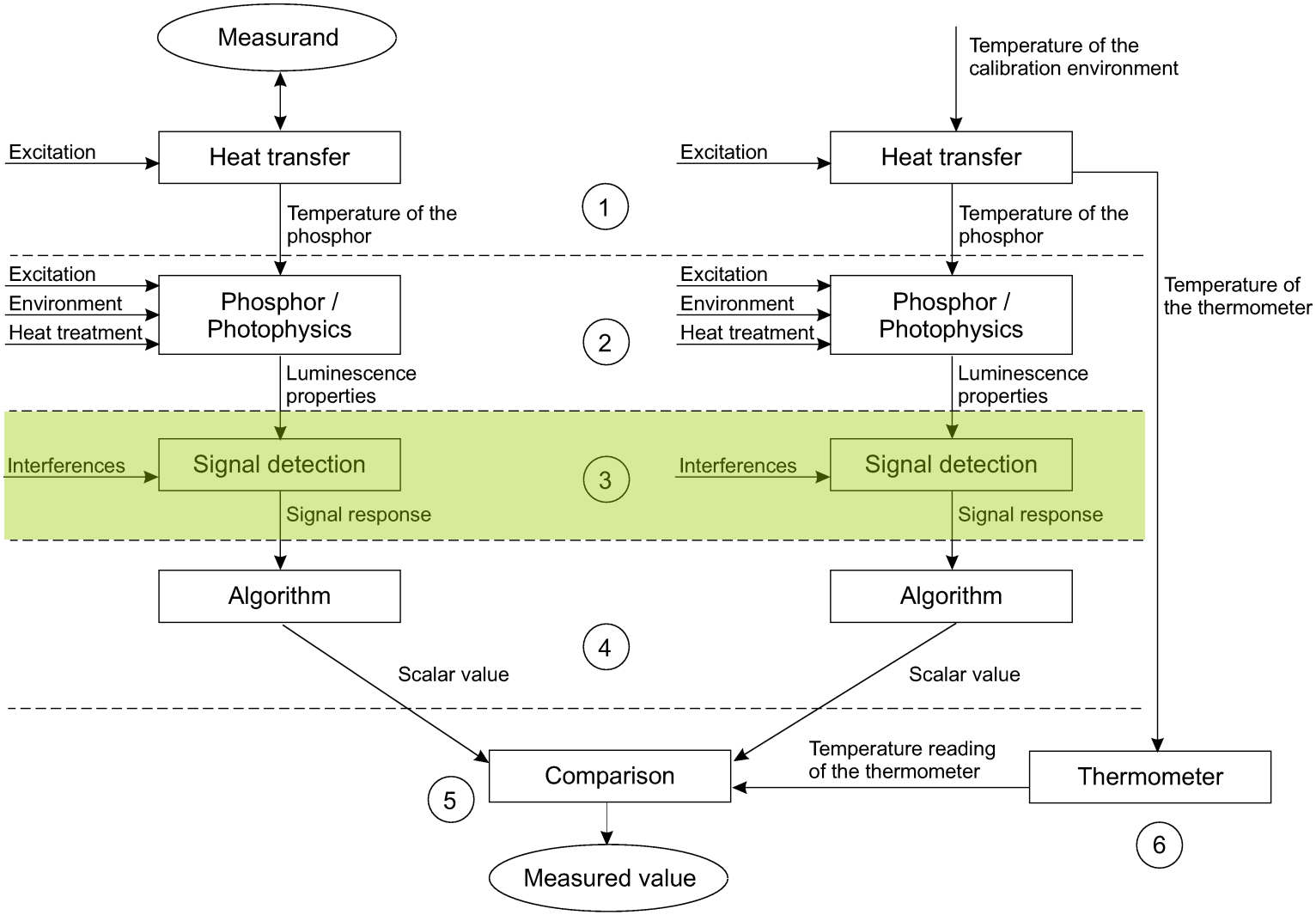


Y_2O_3:Eu

Dependency on the oxygen concentration

Brübach, J.; Dreizler, A.; Janicka, J.: Meas. Sci. Technol., 18(3):764–770, 2007.

Error class 3:
Signal detection



Error class 3:
Signal detection – overview

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- Impact of the transfer function of the detection system
  - ➔ limited spatial, temporal and spectral resolution
  - ➔ nonlinear behaviour of the detector (CMOS camera)
- Parameters that manipulate the transfer function of the detection system
  - ➔ small changes in the alignment (intensity ratio, see PCI 33-paper 2013)
  - ➔ terminating resistor, BNC length, amplifier (PMT, decay time)
- Optical and electrical interferences
  - ➔ optical interf. (e.g. background radiation, CL, fluorescence of substrate,…) most often temporally not correlated (worse precision)
  - ➔ electrical interf. (e.g. high voltage Q-switch electronics) might be temporally correlated (worse accuracy)
- Dynamic DUTs (e.g. moving surfaces)
  - ➔ signal decay might be superimposed by spatial variations of the absolute luminescence intensity; depending on the homogeneity of the excitation irradiance and the phosphor coating as well as on spatial temperature variation

Error class 3:
Signal detection – PMT versus CMOS

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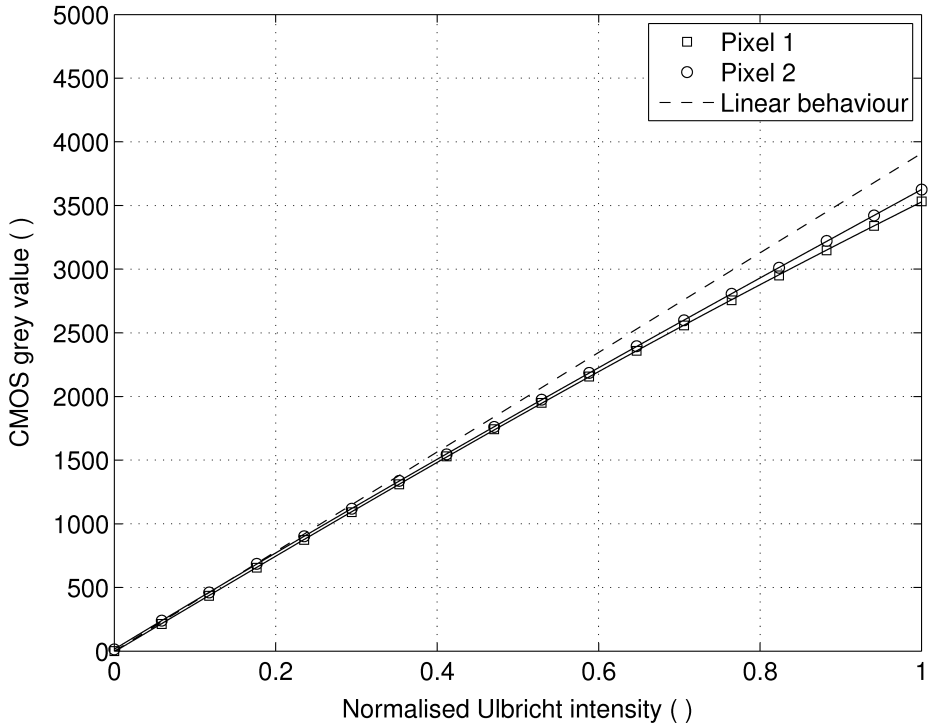
- Photomultiplier unproblematic
- CMOS camera shows problems regarding
  - ➔ Linearity
  - ➔ Pixel-to-pixel homogeneity
  - ➔ Offset stability



Kissel, T.; Baum, E.; Dreizler, A.; Brübach, J.: Appl. Phys. B, 96:731–734, 2009.

Error class 3:
Non-linear detector behaviour

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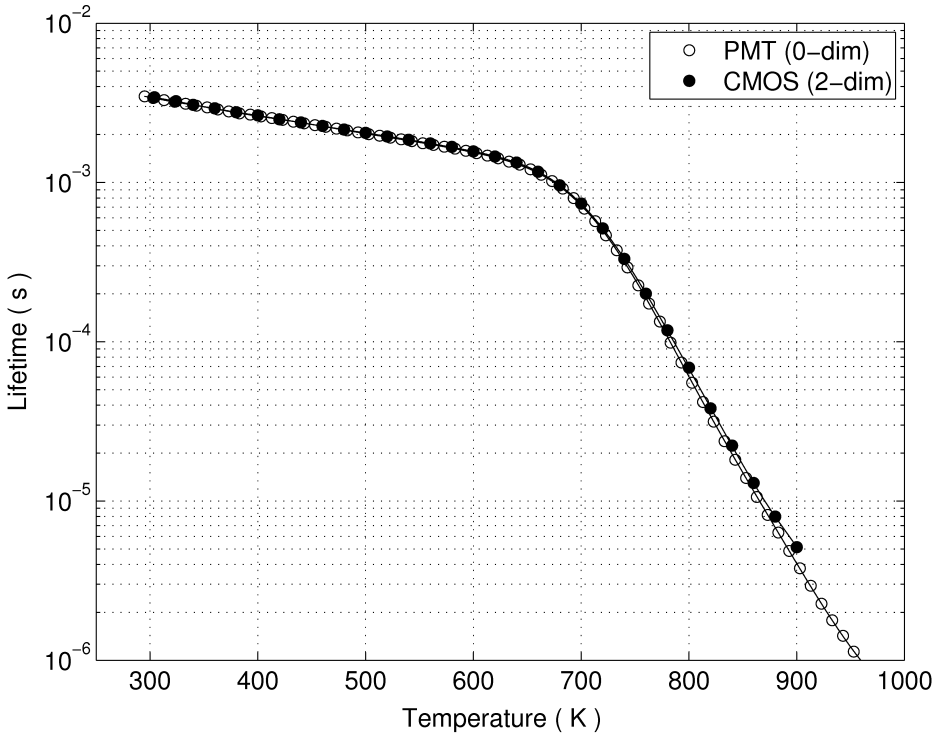
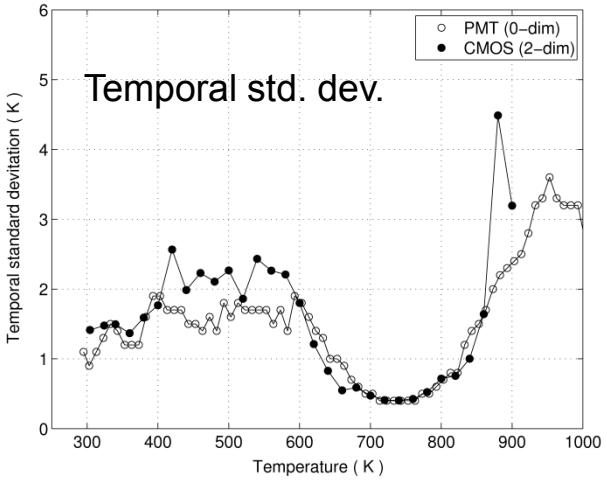
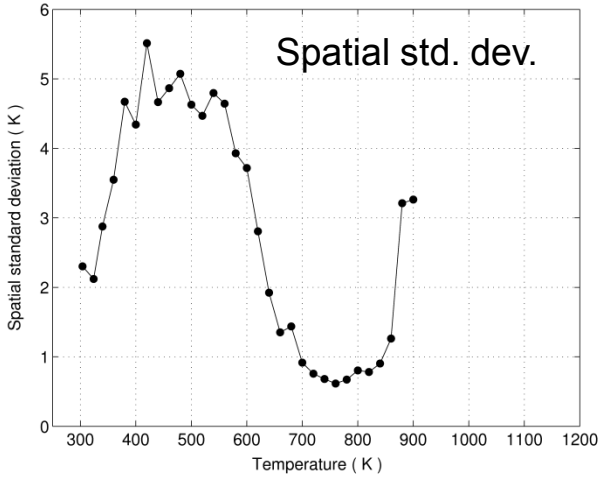
- Correction function for each pixel fixes the problem







Kissel, T.; Baum, E.; Dreizler, A.; Brübach, J.: Appl. Phys. B, 96:731–734, 2009.

Error class 3:
Coating thickness and CMOS frame rate

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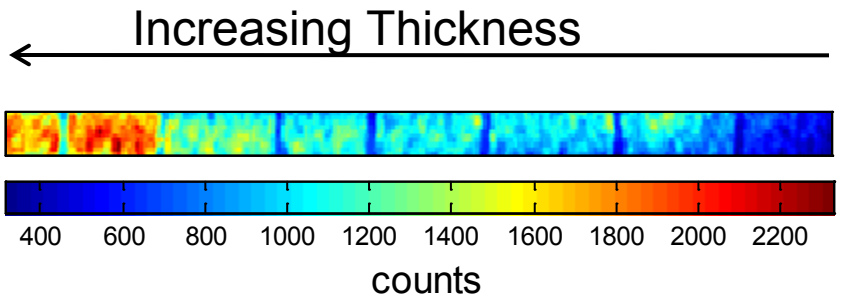
Variation of coating thickness and luminescence intensity

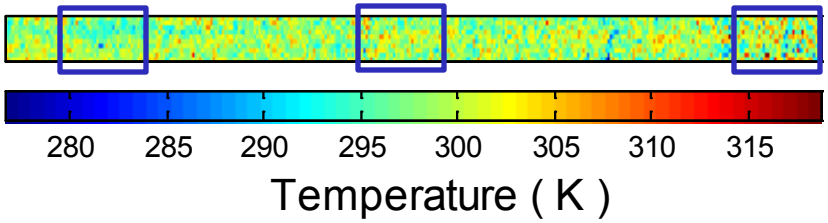


Resulting Temperature:

299,4 K ±3,0 K

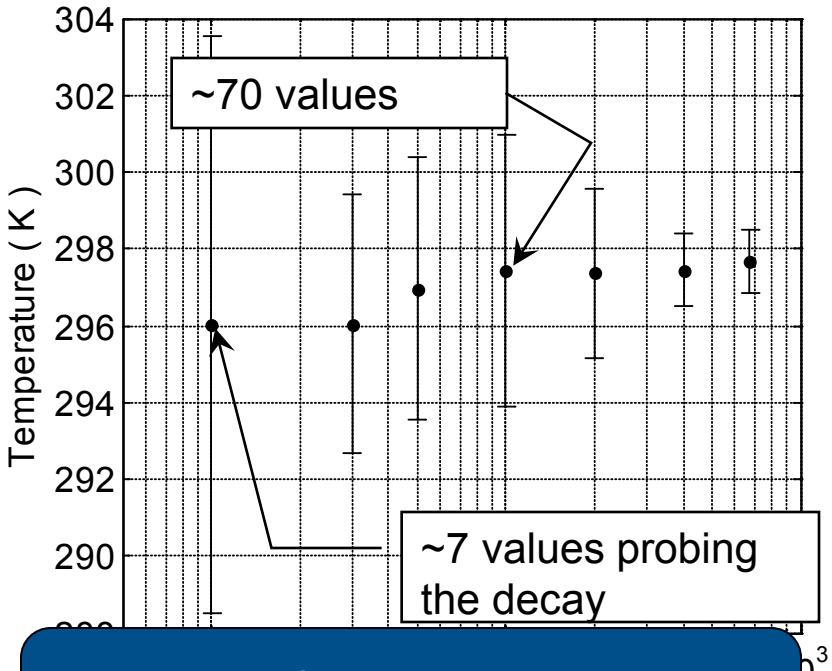
298,0 K ±3,3 K

297,4 K ±5,7 K



No significant influence!

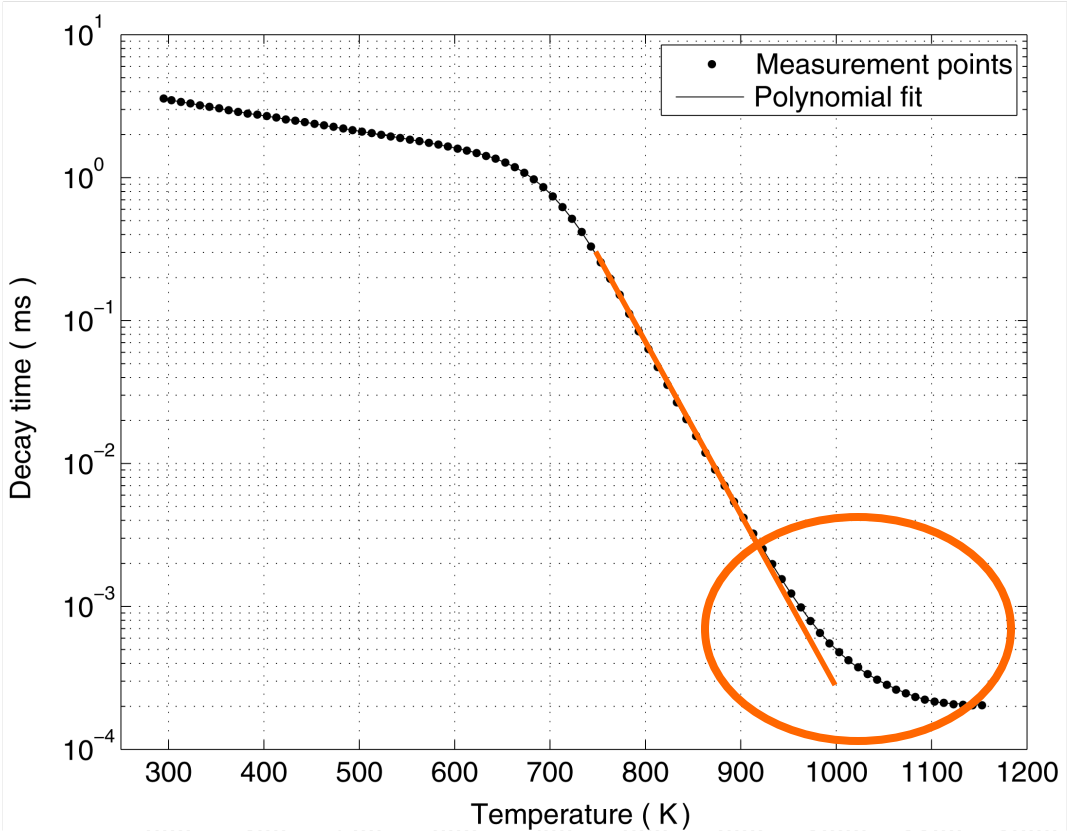
Variation of frame rate:



Minimum of standard deviation at high temporal discretisation.

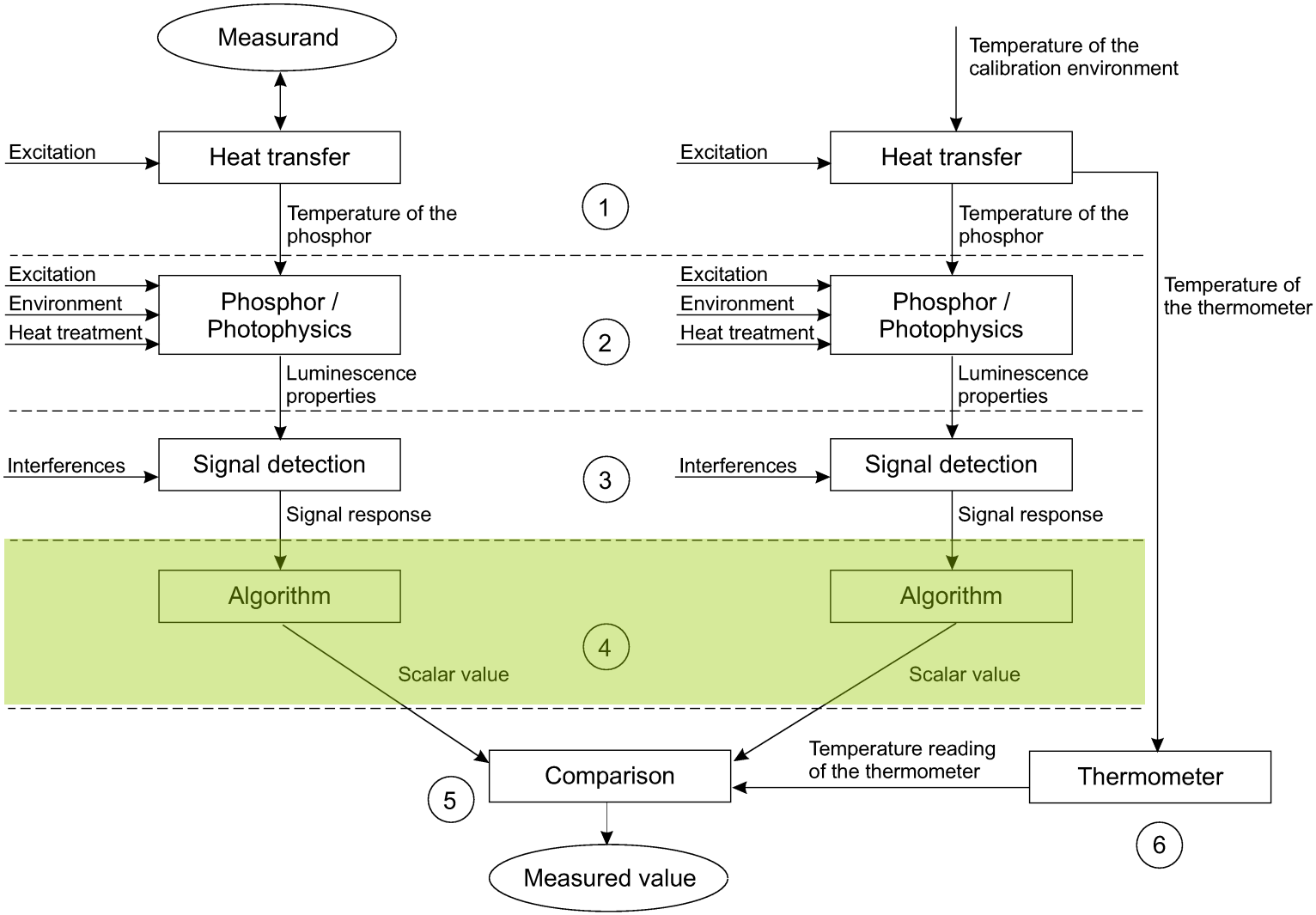
RSM

Error Class 3:
Parameters impacting the transfer function



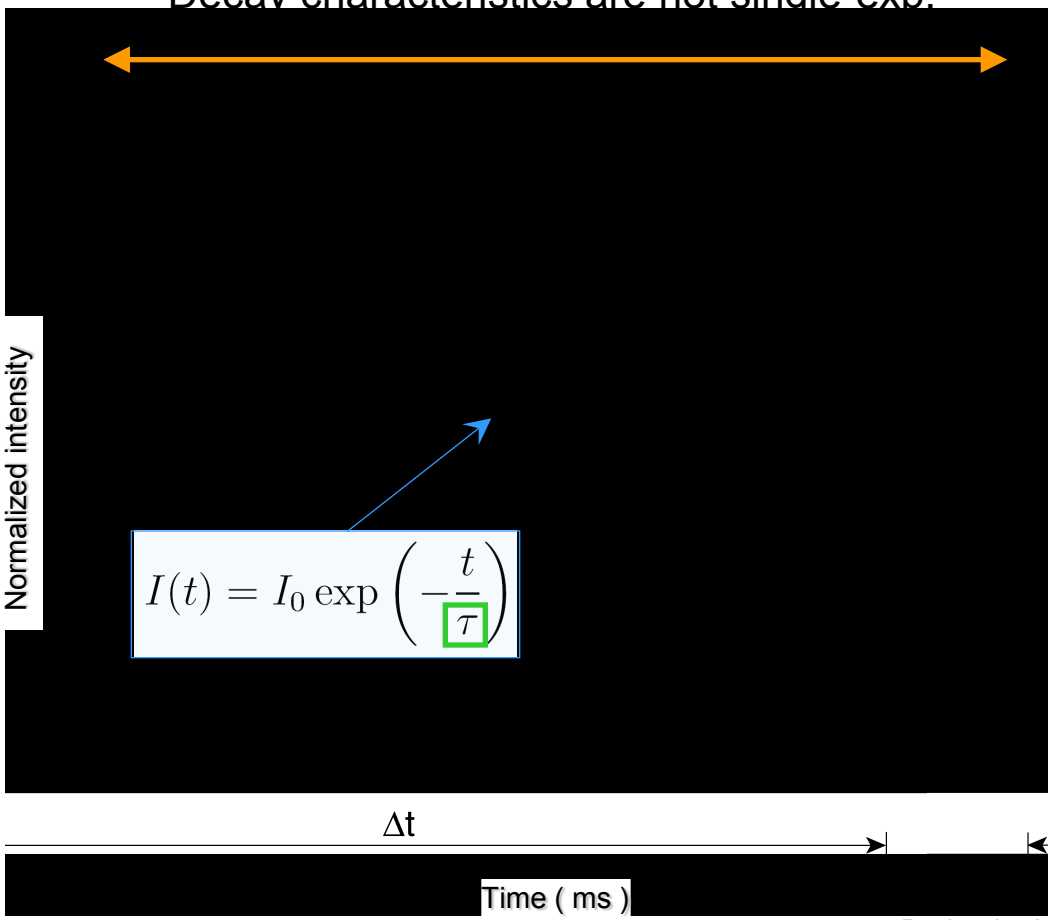
- ➔ Modified low pass character of the detection system (PMT) due to terminating resisitor
- ➔ might strongly change the calibration curve, especially at low decay times

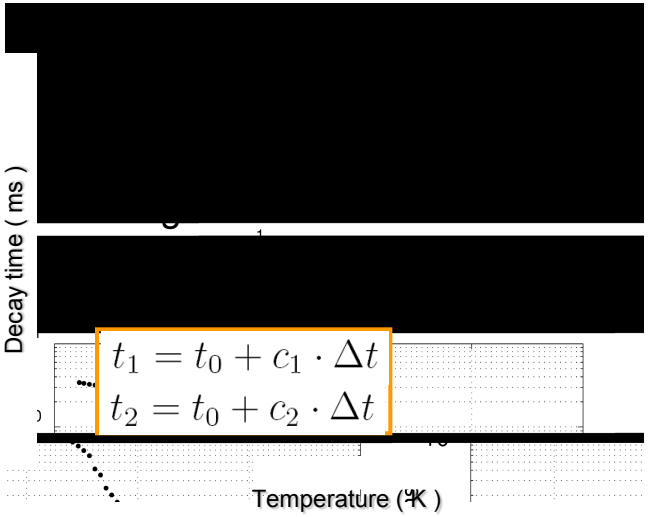
Error class 4:
Algorithm for the data reduction

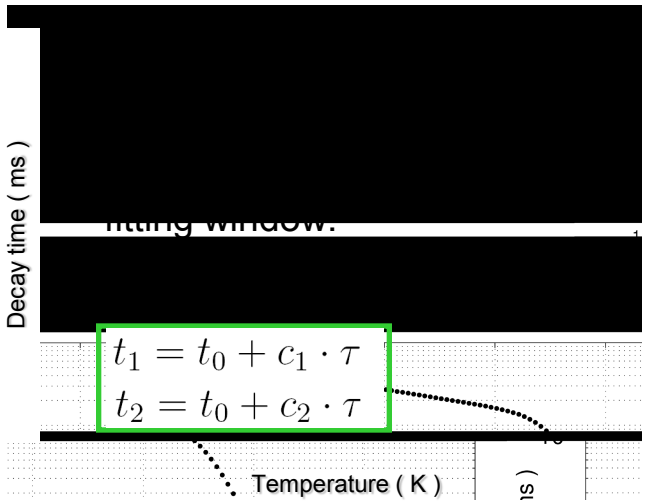


Error class 4:
Algorithm for the data reduction

Problem:
Decay characteristics are not single-exp.

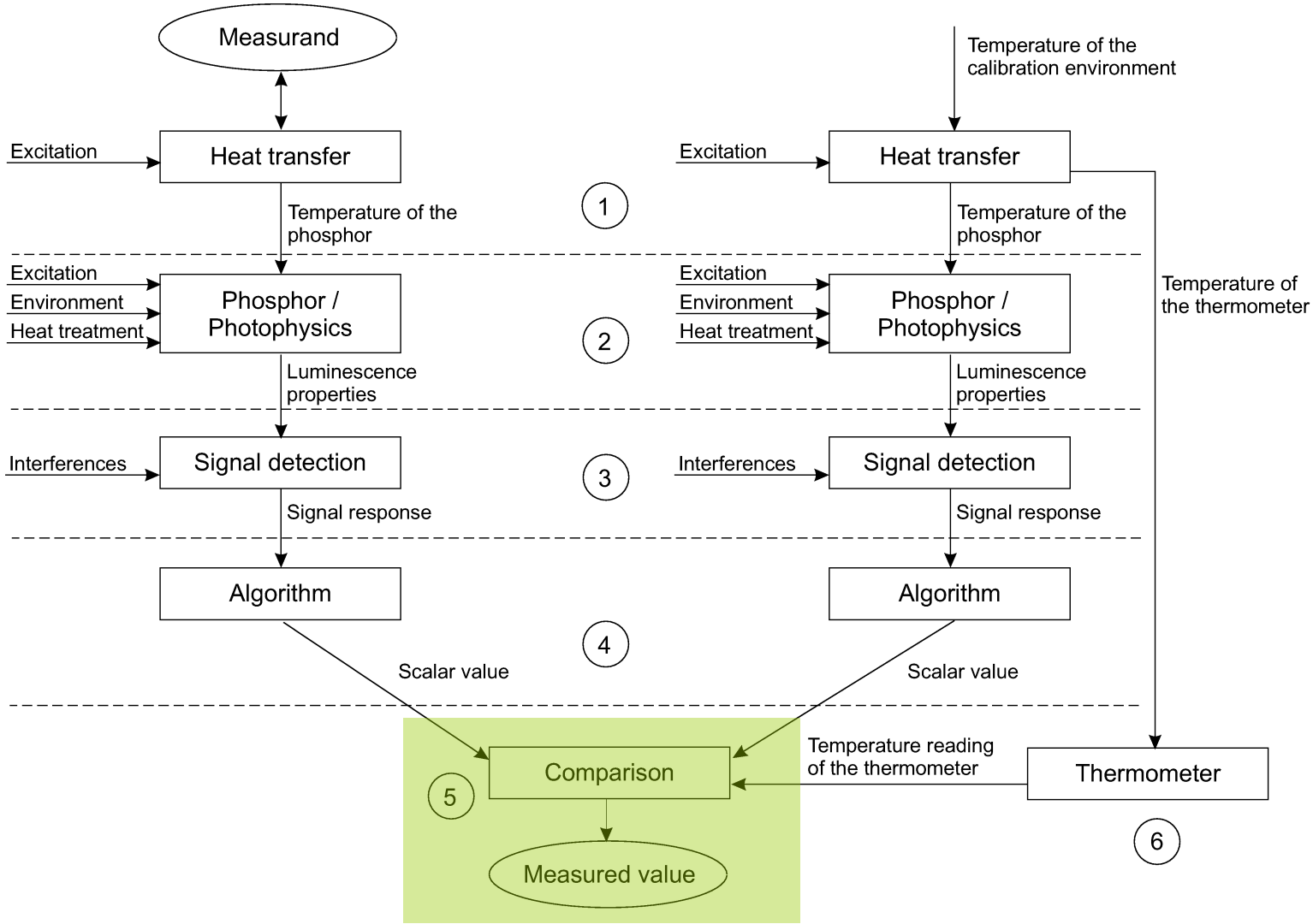






Brübach, J.; Janicka, J.; Dreizler, A.: Opt. Laser Eng., 47(1):75–79, 2009.

Error class 5:
Comparison of the scalar values



Error class 5:
Comparison of the scalar values

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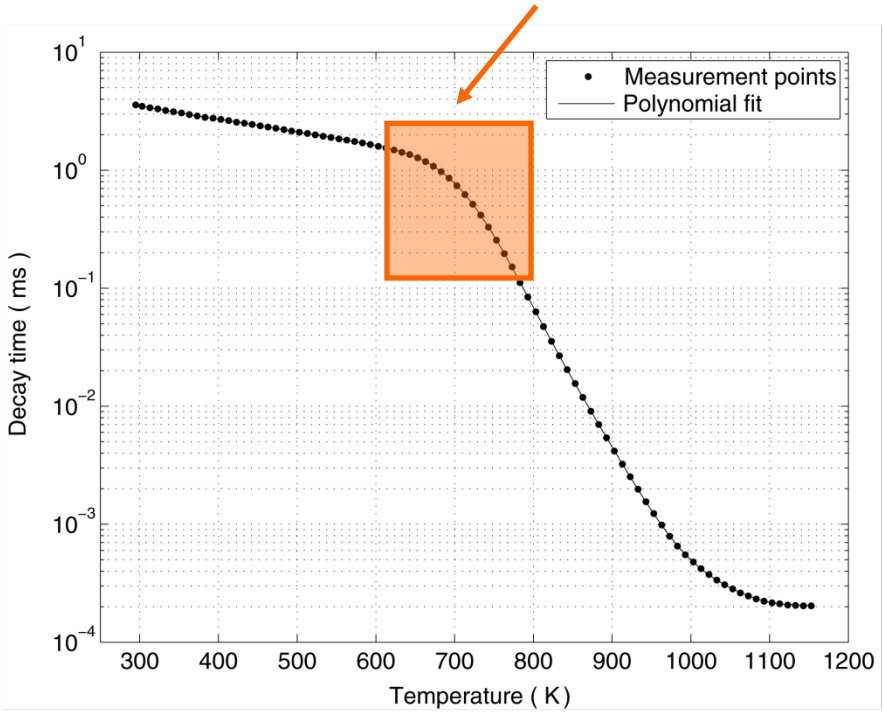
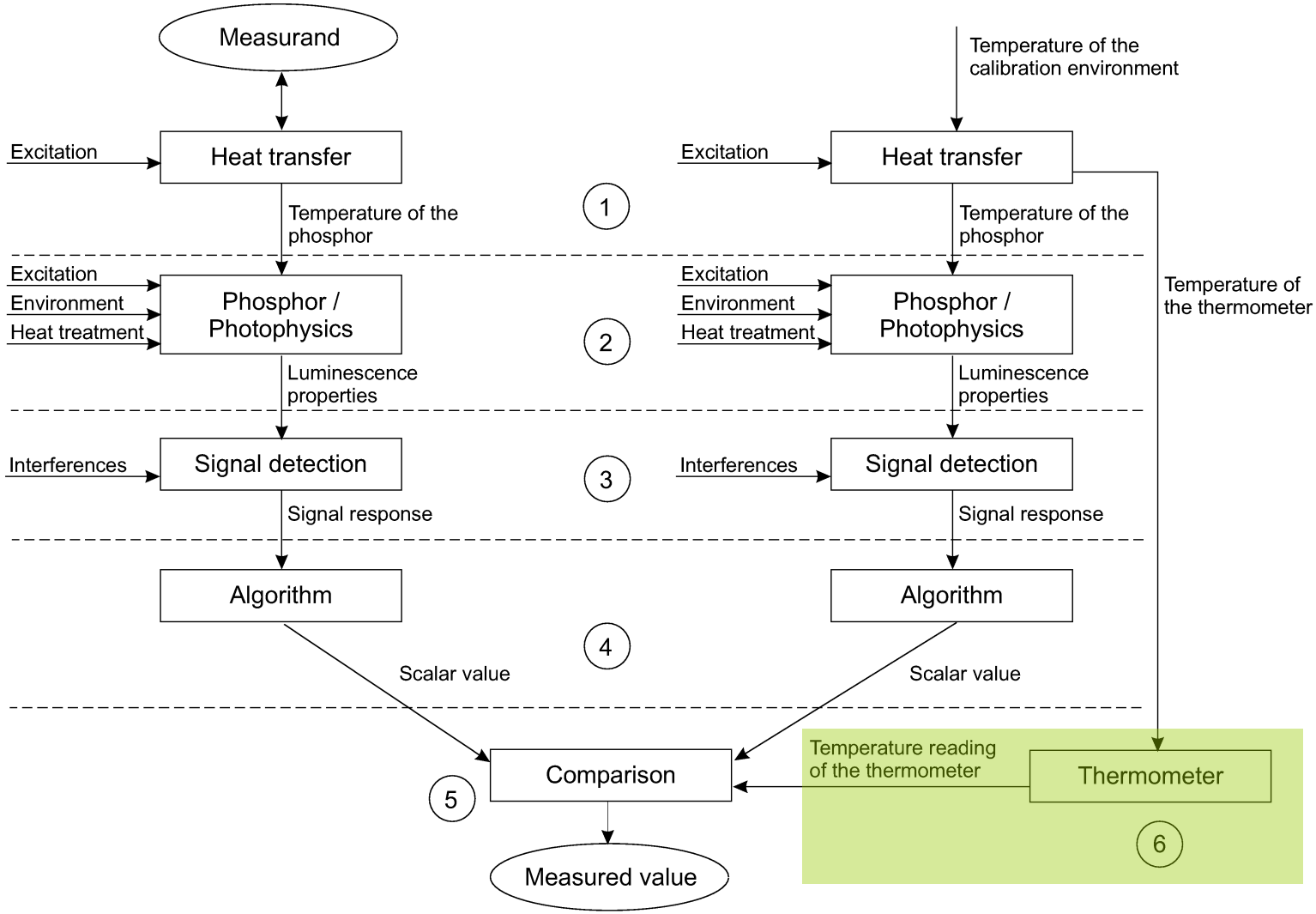
- Error depending on the calibration temperature intervals and the quality of the interpolation in between the calibration points.
- High error potential in strongly curved regimes of the calibration curve



- Calibration intervals of at least ΔT = 20K or even ΔT = 10K are recommended.

Error class 6:
Uncertainty of the calibration thermometer



Error class 6:
Uncertainty of the calibration thermometer

- Most often, thermocouples are employed

- High quality thermocouples offer an accuracy of better than 0.4 % of the absolute temperature.

Error Review

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Provided a careful practice:
→ Systematic Error < 1 %

Systematic Error:

Error class		max. error
1. Heat transfer		?
2. Photophysics	Excitation	$O\,(10^1\,\mathrm{K})$
	Dopant concentration	$O\,(10^2\,\mathrm{K})$
	Heat treatments	$O\,(10^1\,\mathrm{K})$
	Surrounding gas phase	$O\,(10^2\,\mathrm{K})$
3. Detection system		$O\,(10^2\,\mathrm{K})$
4. Algorithm for data reduction		$O\,(10^1\,\mathrm{K})$
5. Comparison of calibration and measurement		$O\,(10^1\,\mathrm{K})$
6. Accuracy of the calibration thermocouple		$O\,(10^0\,\mathrm{K})$

Statistical Error:

Shot-to-shot standard devitation: approx. 2 K

Brübach, J.; ISA 55th Int. Instrumentation Symposium, 2009

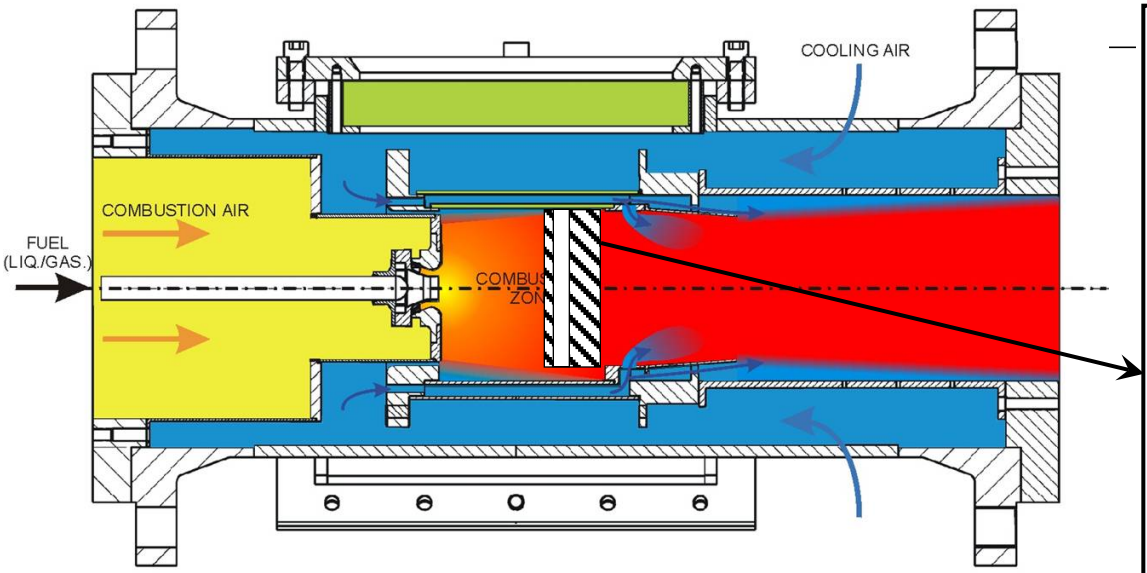
1. Introduction

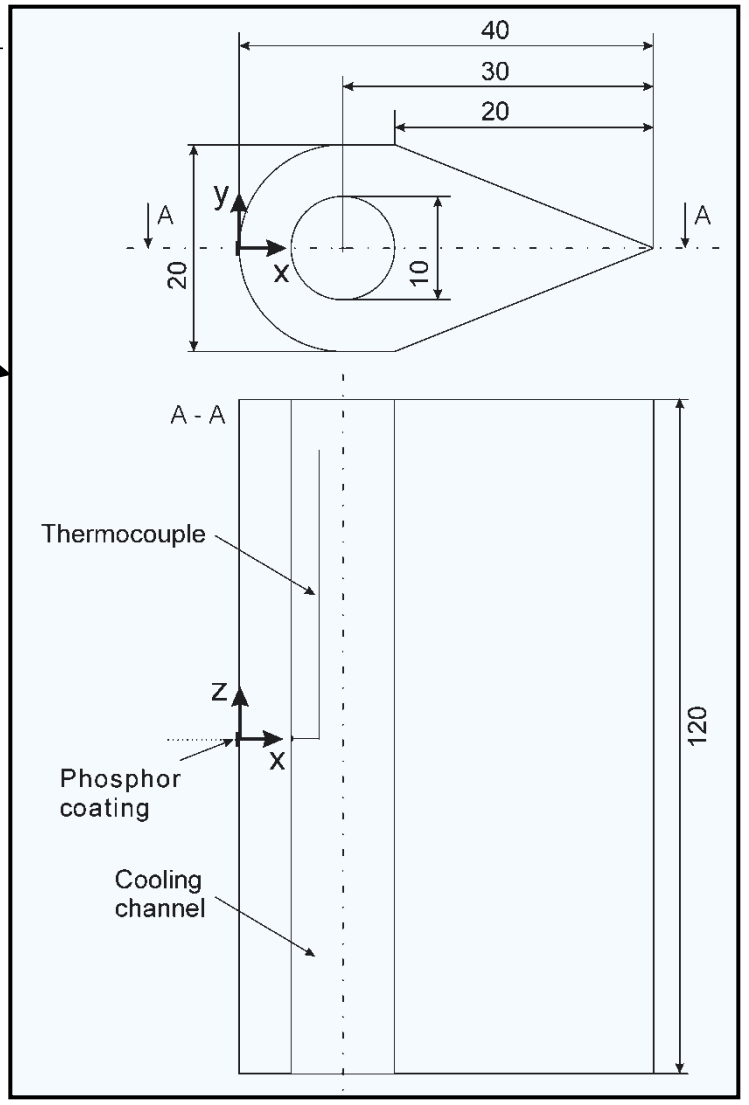
2. Measurement chain / Error sources

3. Applications

4. Summary

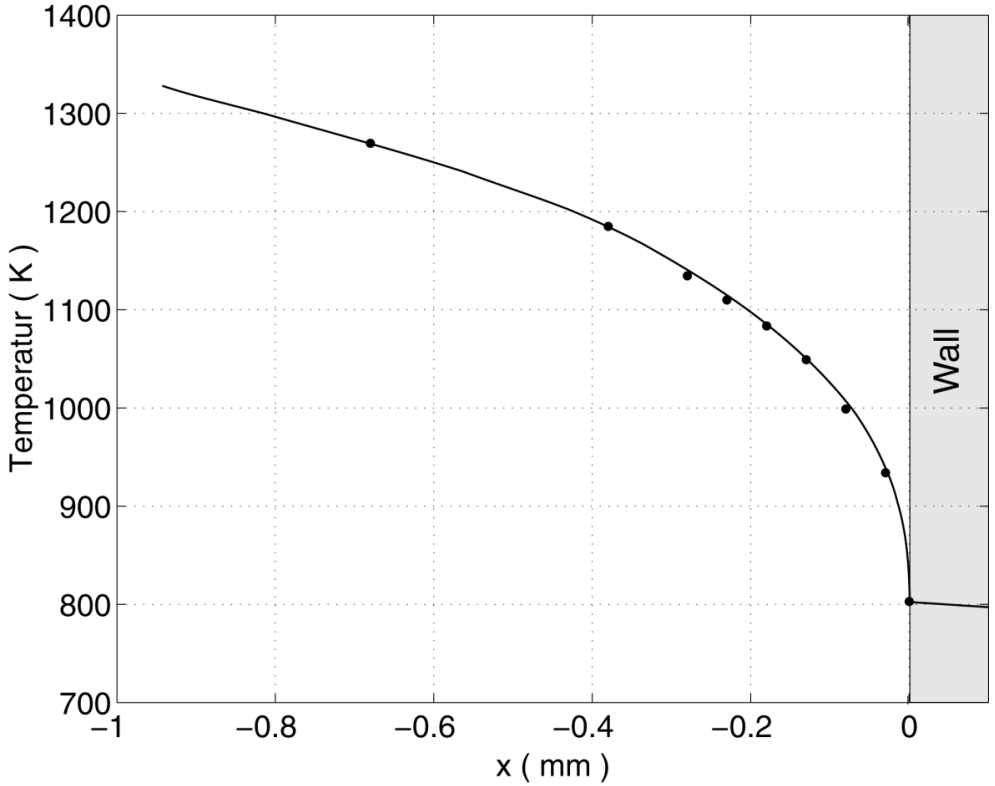
Optically accessible combustor





Nozzle	Air-blast atomizer (MTU)
Fuel	n-heptane at T = 368 K, 1.49 g/s
Combustion air	Preheated at T = 623 K, 24.9 g/s
Pressure	p = 2 bar
Equivalence ratio	ϕ = 0.9
Thermal power	P = 67 kW

Optically accessible combustor



- Distance of the probe volume next to the wall: 30 µm
- Temperature progression of the gas phase can be extrapolated very well to the wall

Brübach, J.; Hage, M.; Janicka, J.; Dreizler, A.: Proc. Comb. Inst., 32(1):855-861, 2009.

Optically accessible combustion engine

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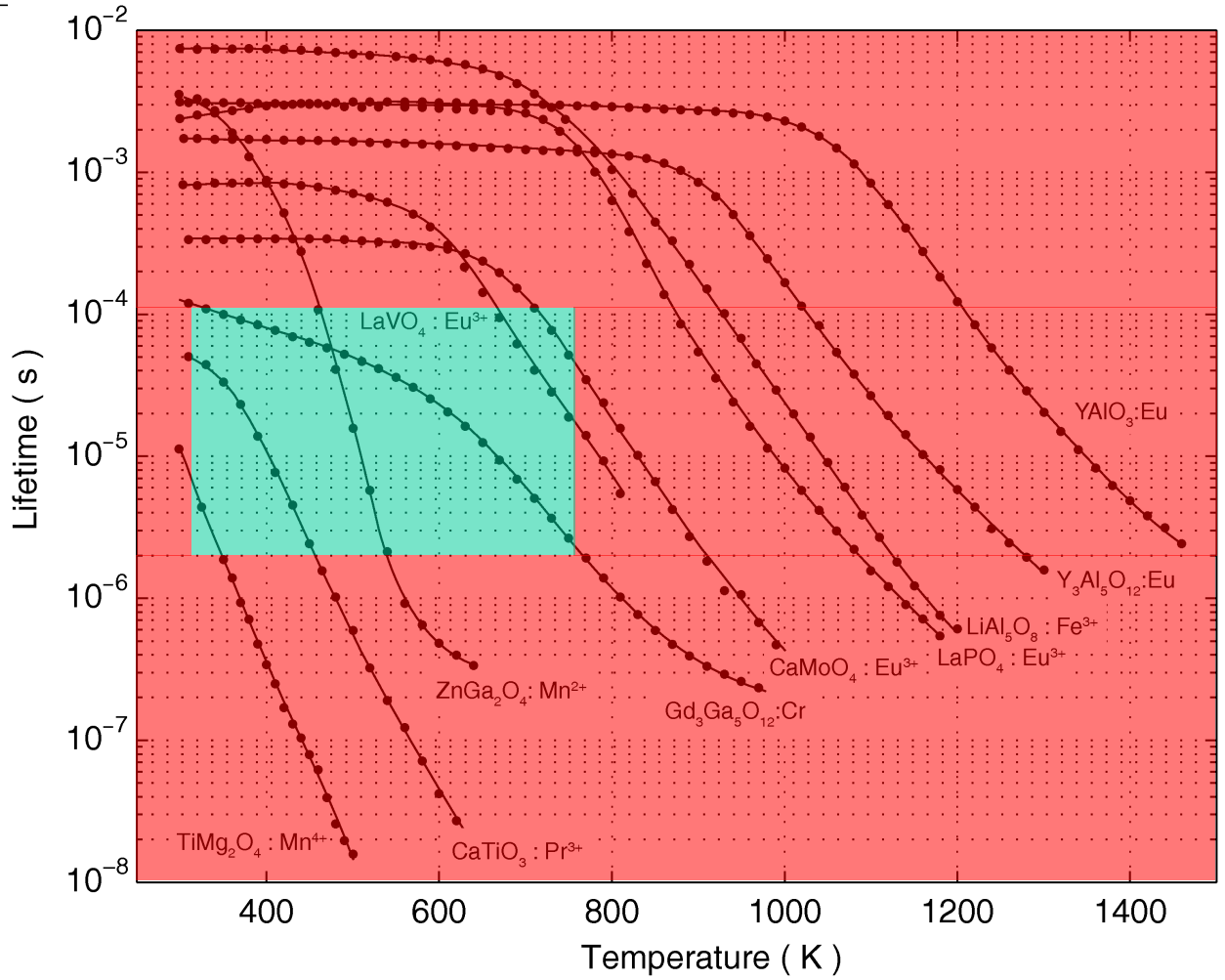
CMOS

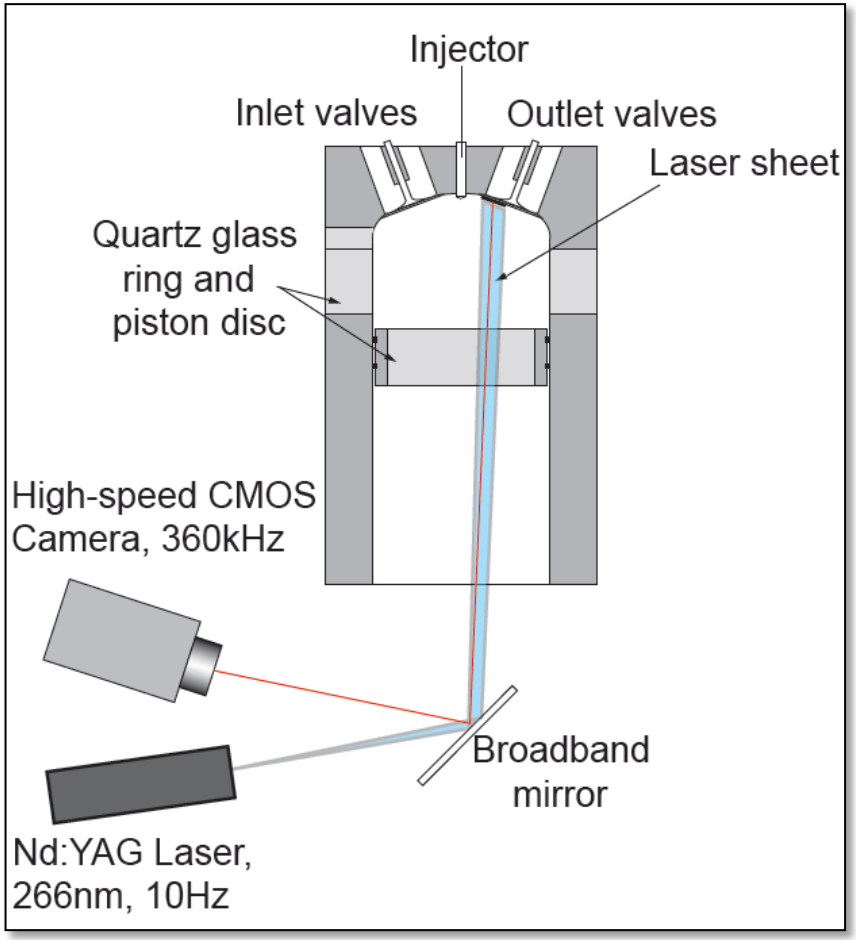


Fuhrmann, N. ; Kissel, T. ; Dreizler, A. ; Brübach, J. : Meas. Sci. Technol., Meas. Sci. Technol.22 045301 (2011)

Brübach, J. ; Kissel, T. ; Frotscher, M. ; Euler, M. ; Albert, M. ; Dreizler, A. : J. Lumin., 131, 559 – 564 (2011)

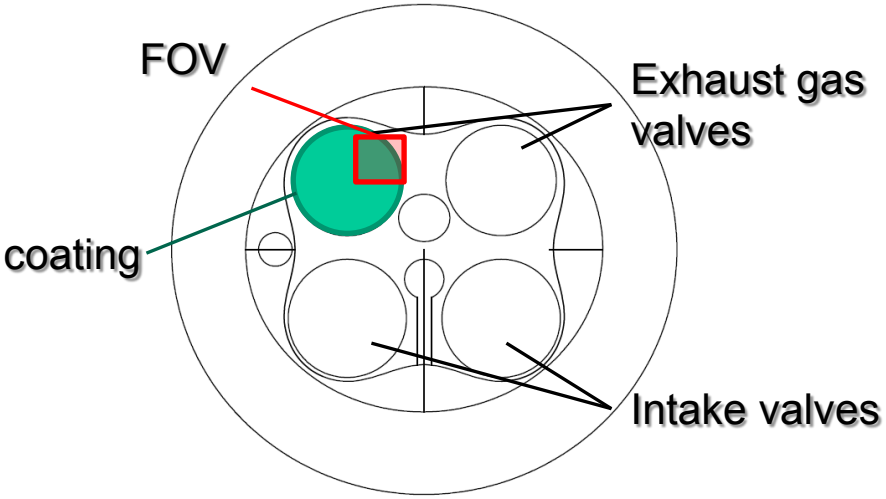
Optically accessible combustion engine

See Appl. Phys. B 2011, Fuhramnn et al.



Temperatur at exhaust valve:

- DI-ICE @ 2000 min^{-1}
- Coating: $Gd_3Ga_5O_{12}$:Cr + Ulfalux Ofenlack
- Spatial resolution: 188 µm/Pixel @ 64x64 Pixel (360 kHz framerate)



Optically accessible combustion engine

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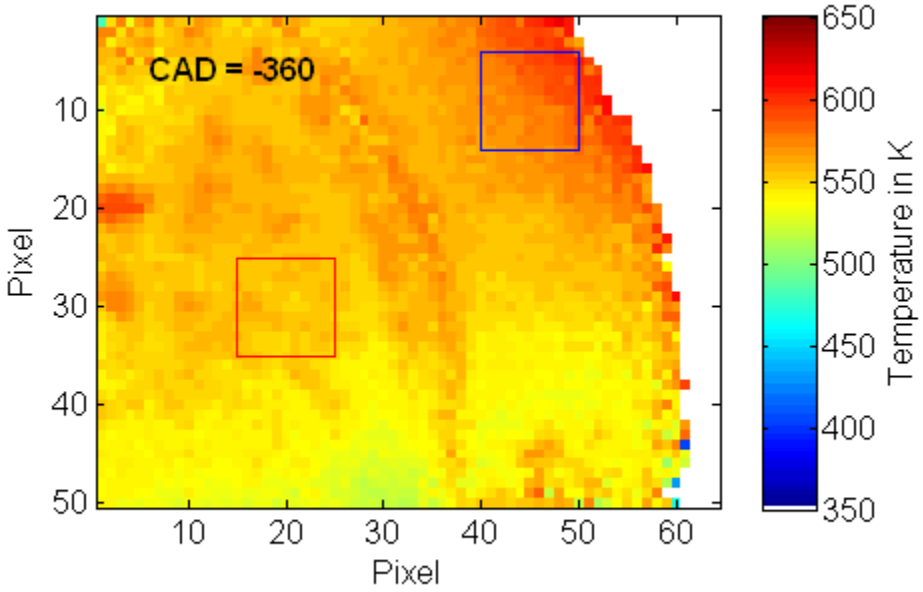
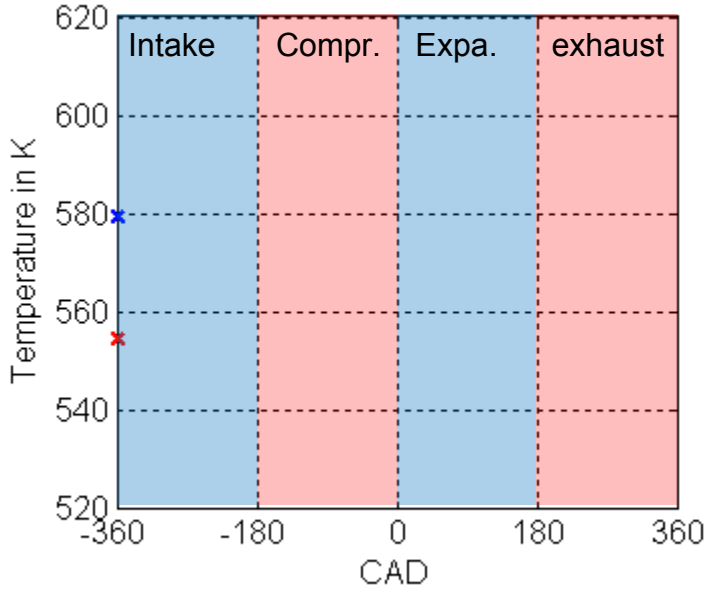
Fired engine operation:

- Temperature measurement at selected CAD





N. Fuhrmann, M. Schild, D. Bensing, S.A. Kaiser, C. Schulz, J. Brübach, A. Dreizler: *Two-dimensional cycle-resolved exhaust valve temperature measurements in an optically accessible internal combustion engine using thermographic phosphors;* Applied Physics B, DOI 10.1007/s00340-011-4819-2.

Extension to high speed phosphor thermometry in ICE

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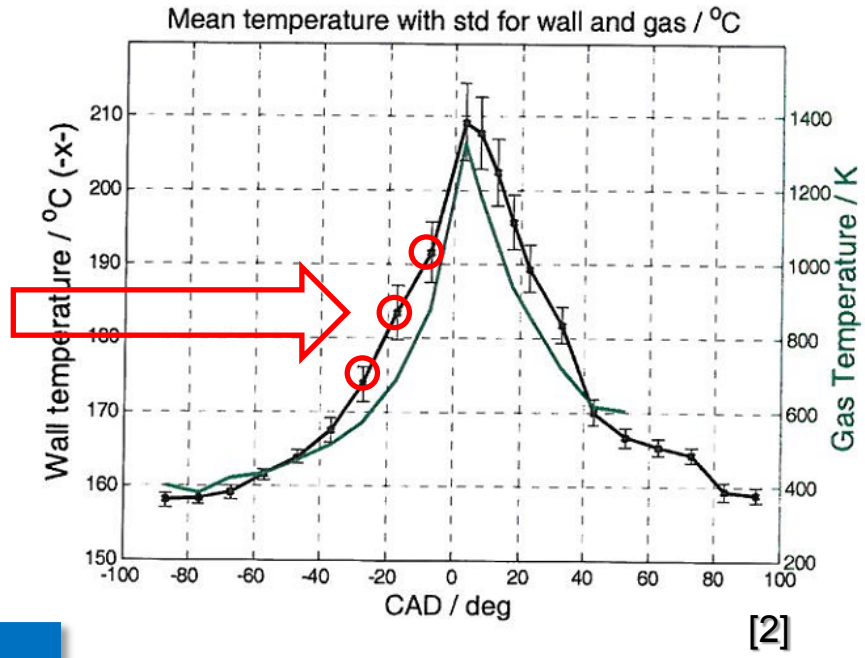
- Former measurements use 10Hz laser-systems for phosphor thermometry
- Temperatures originate from different cycles → averaging of uncorrelated single shots



[2]

High speed phosphor thermometry

Use laser at high repetition rate to resolve temperatures within cycles

Resolving singly cycles by high speed TGP

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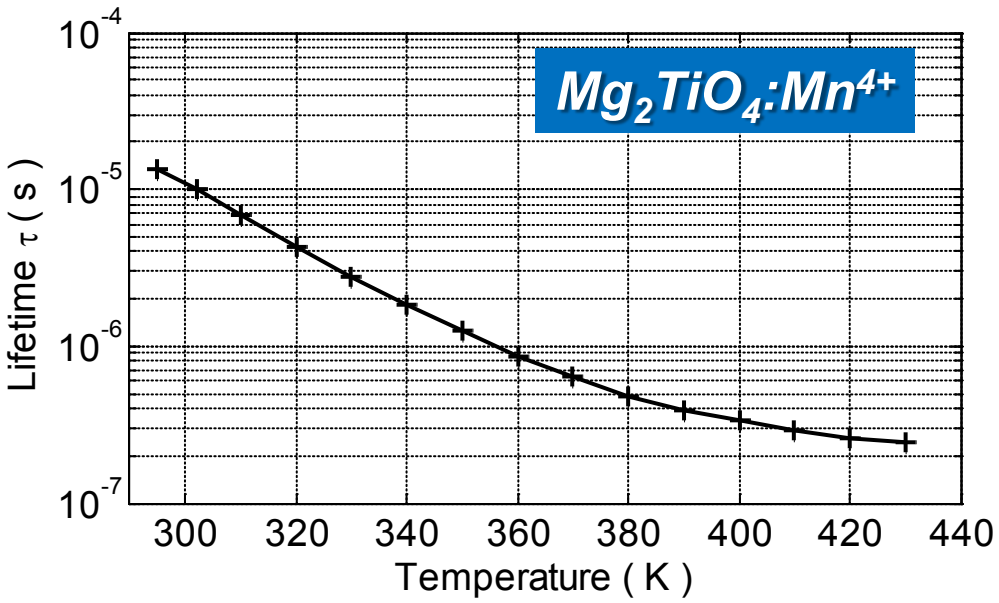
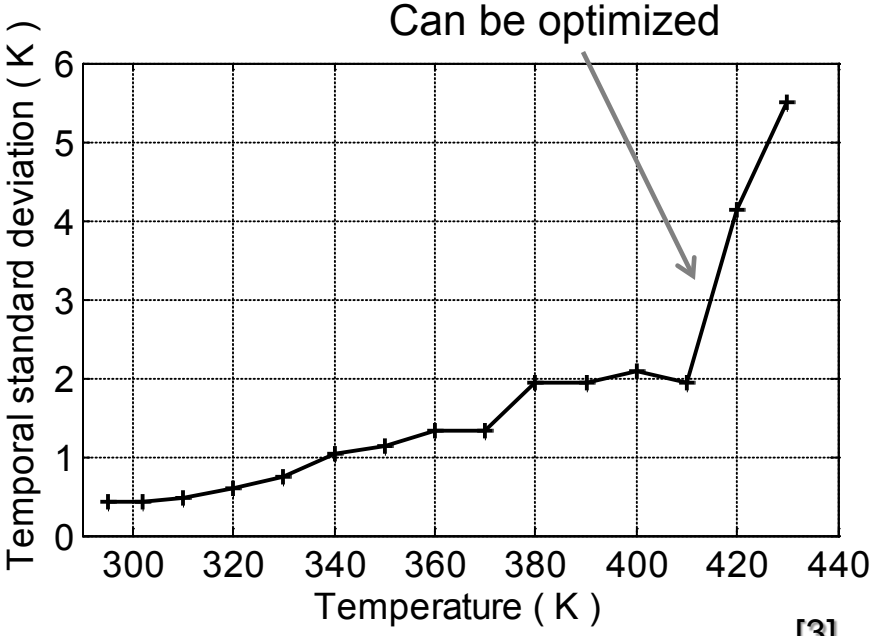
- High speed phosphor thermometry
- Very fast decaying phosphors
- Well below 167µs (1°CA at 1000 rpm)



Steep increase due to detection system Can be optimized



[3]

Influence of laser-induced heating

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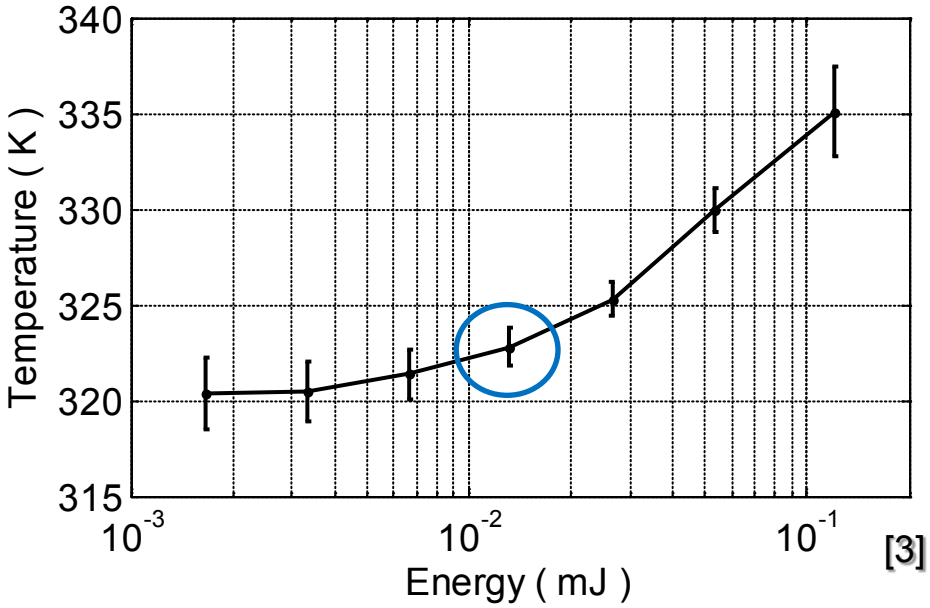
- Challenges when using High Speed Phosphor Thermometry:
- → Laser-induced heating effects

- Due to high power delivered by laser
- Quantify by energy-scan
- Trade-off between precision and accuracy



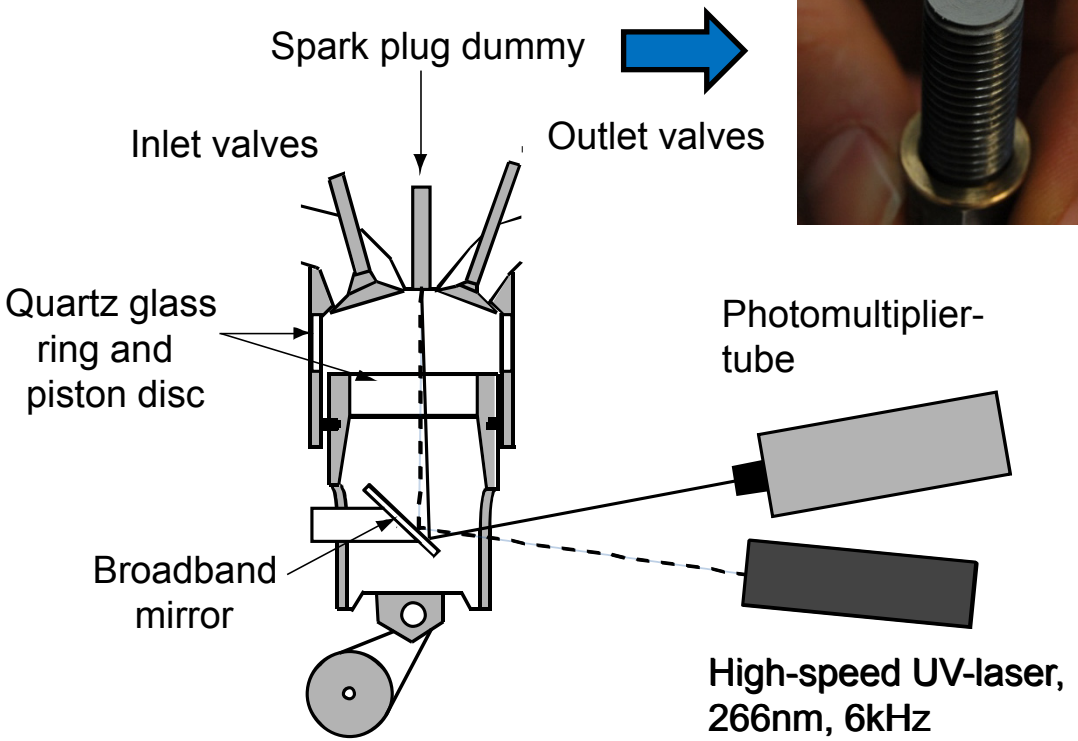
Optimum at E = 13µJ :

Standard deviation below 1K

Systematic error of 2.5K

Set-up and realization

- Experimental Setup



Coating

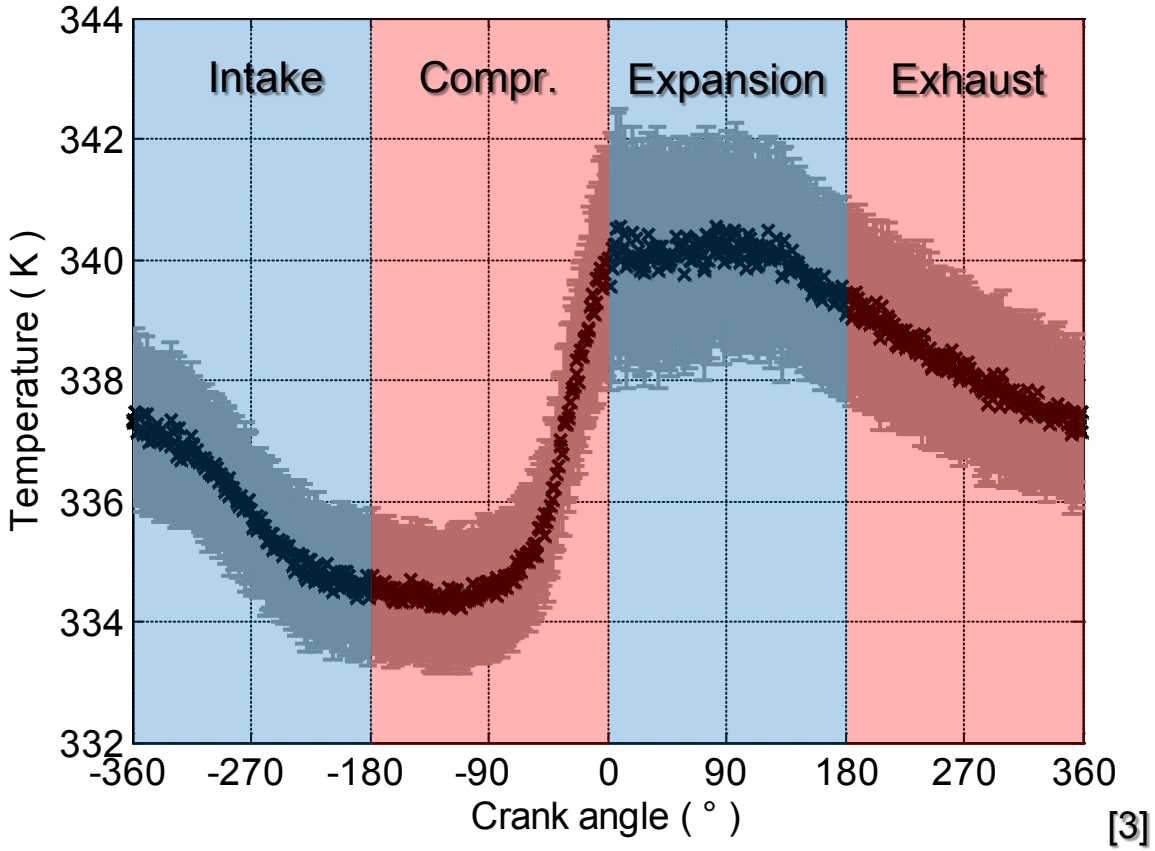
- Coated via airbrush
- Dispersion of binder and phosphor

Engine

- Motored at 1000rpm
- No injection and ignition
- Compression ratio 8.5:1

Results for motored engine (no combustion)

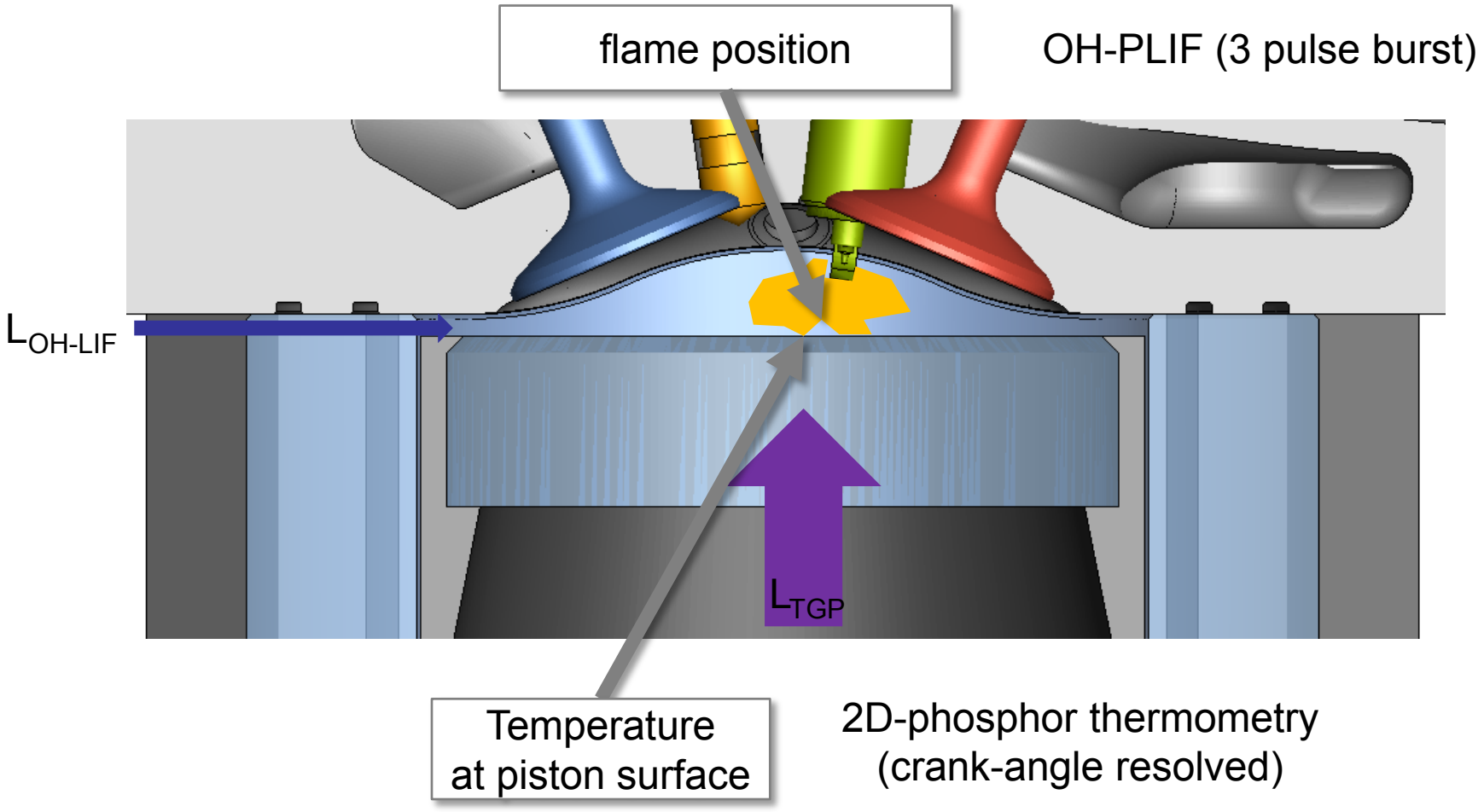
- Temperature progression of the spark plug dummy



[3]

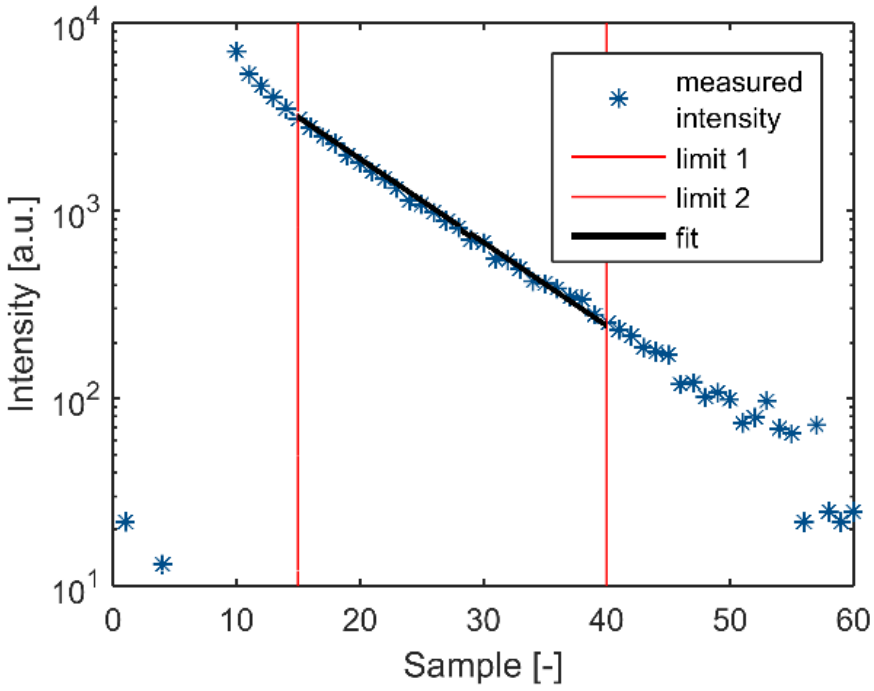
- Mean values and temporal standard deviations of 100 cylces
- Resolution of 1 ° CA
- Precision of about 1-2 K

Wall temperature measurements during flame wall interactions in IC engine

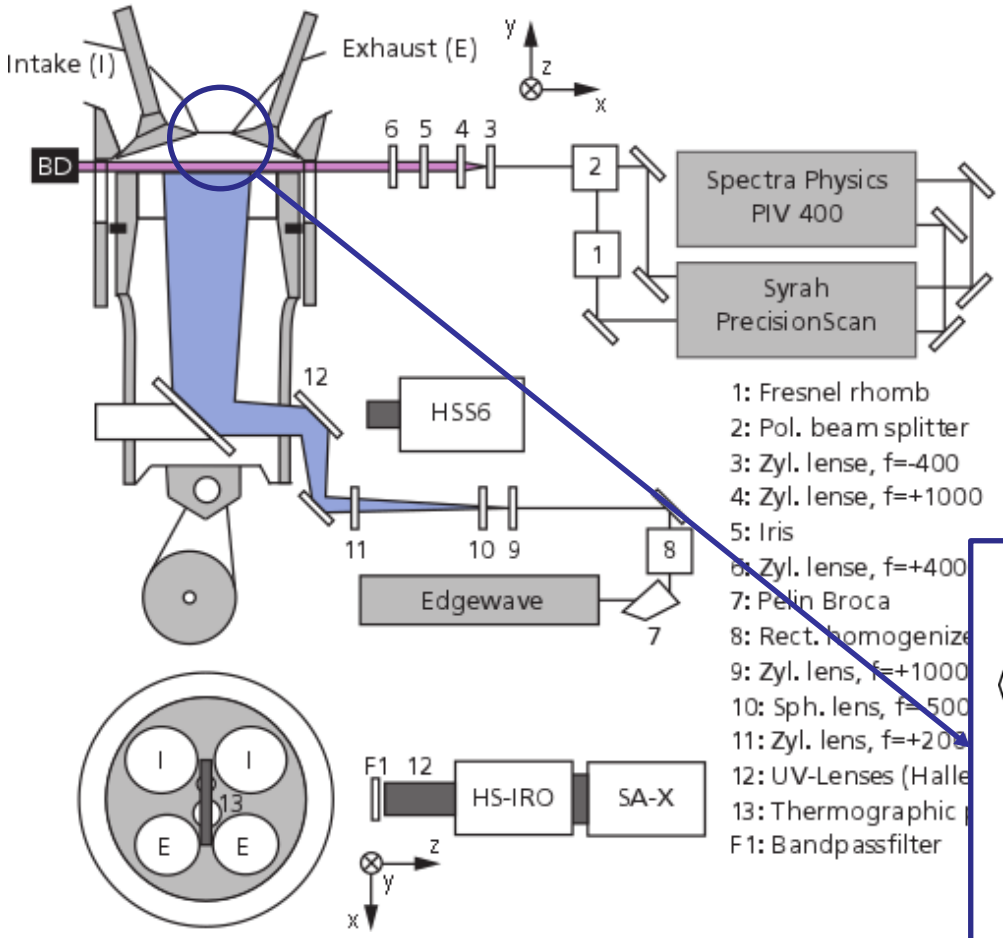


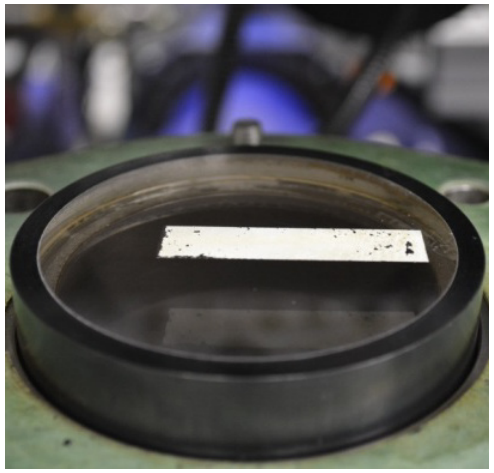
Phosphor thermometry

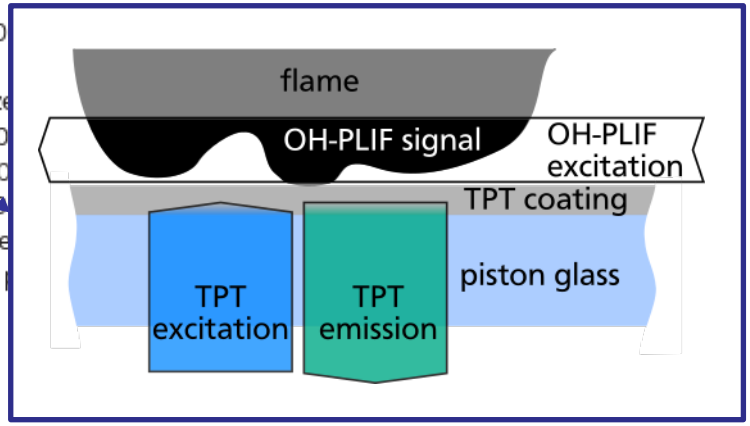
- Decay-time method
  - Ex-situ calibration
- Engine requirements
  - Fast temperature measurements (~ 10µs)
  - High sensitivity, high SNR (~ 5K)
- Suitable thermographic phosphor: $Gd_3Ga_5O_{12}$:Cr,Cer



Experimental setup for studying flame-induced heating





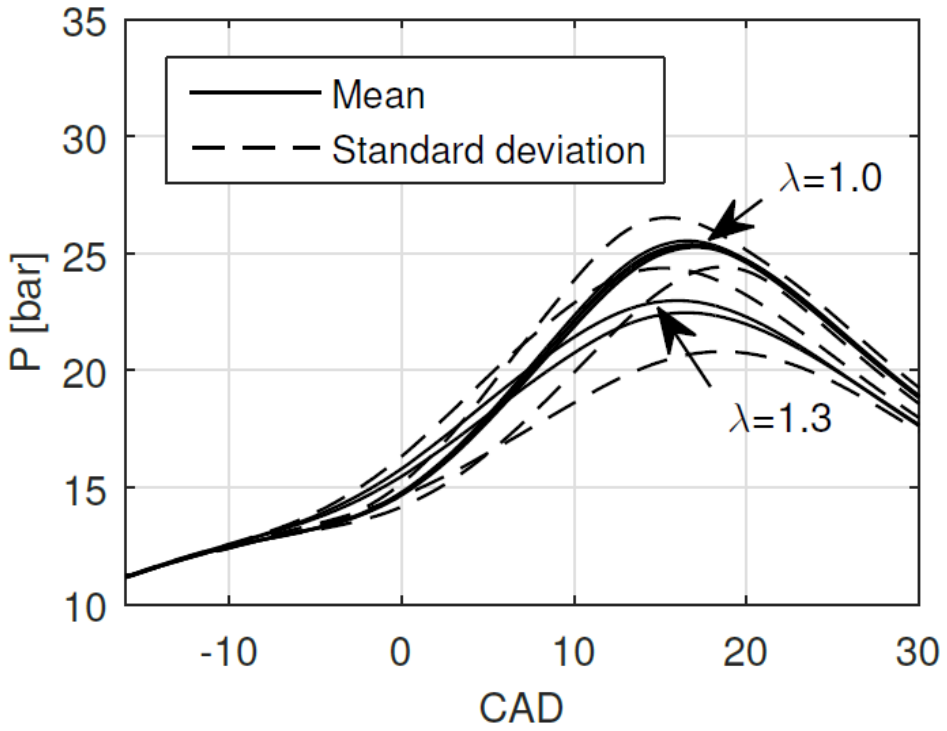


Engine operational conditions

Heating up the engine for several runs → multiple runs recorded

300 cycles	100
Operating Point	fired

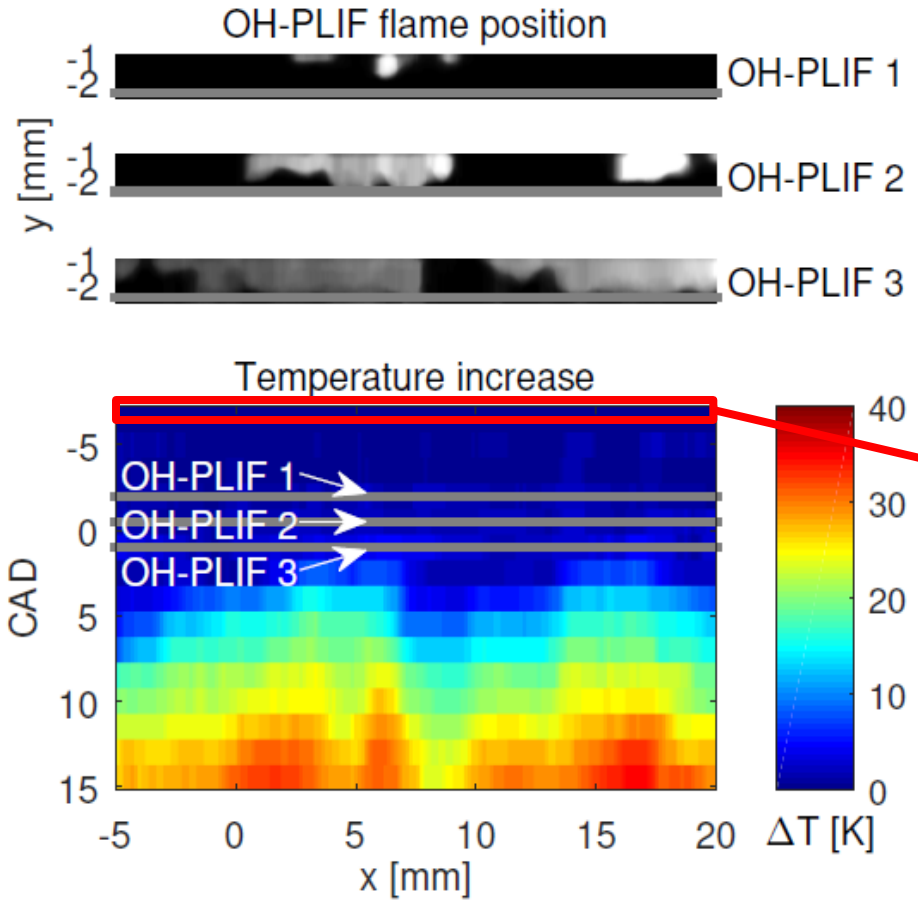
fuel	CH_4
p_{in}	950 mbar
T_{in}	32°C
Speed	800 rpm
Imep	5.3 bar
lambda	1.0 and 1.3
$t_{ignition}$	-11 and -16 CAD aTDC



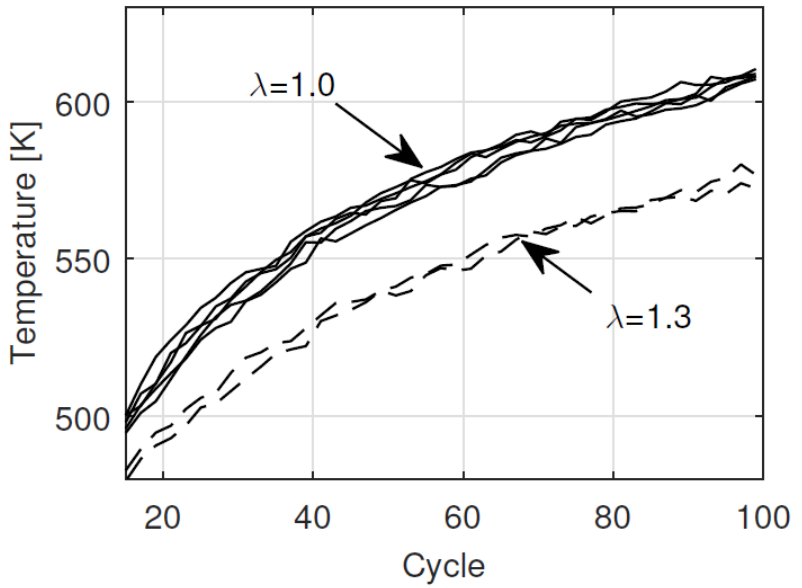
HS-TPT

OH-PLIF: 3 Images at -2, -0.5 and 1.0 CAD aTDC

Flame position and wall temperature

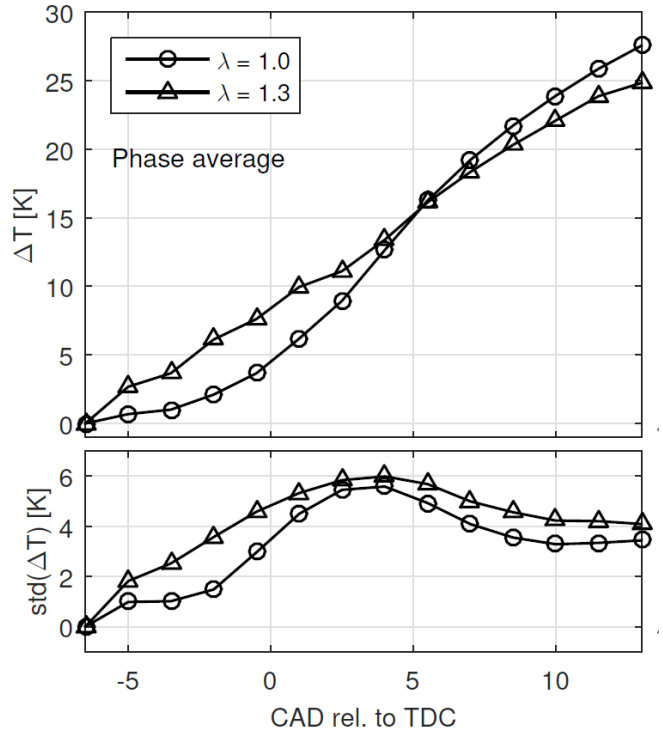


- coherence of flame impingement and wall temperature increase
- reproducible temperature evolution

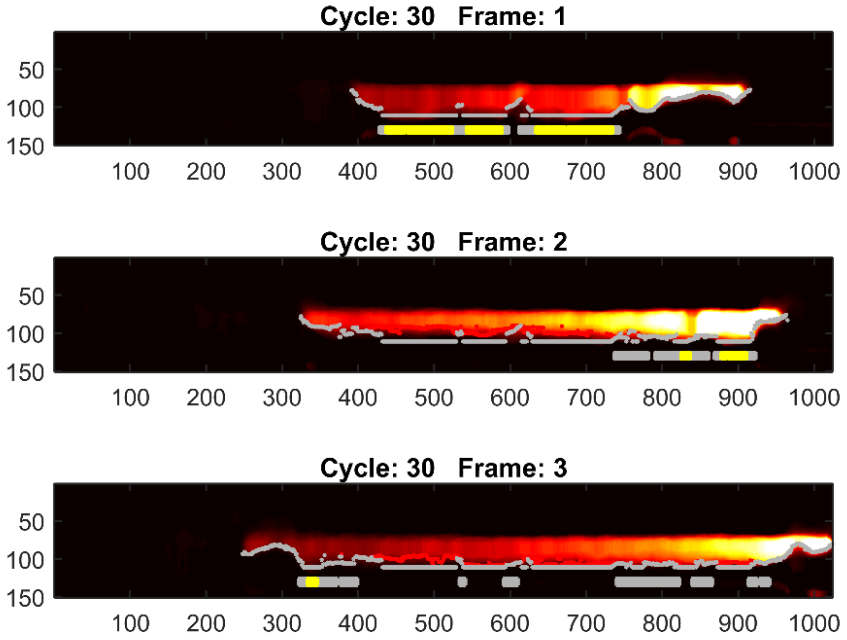


Temperature rise during flame-wall interaction

Phase averaged



Conditional averaged



- Maximum heating rates of up to 20,000 K/s

1. Introduction

2. Measurement chain / Error sources

3. Applications

4. Summary

Summary

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- Systems for 0D und 2D phosphor thermometry
- Decay-time method superior compared to ratio method with respect to precision and accuracy
- Quantification of systematic and statistic error
- Application (relatively) straight forward, even to complex systems
- High potential for further applications

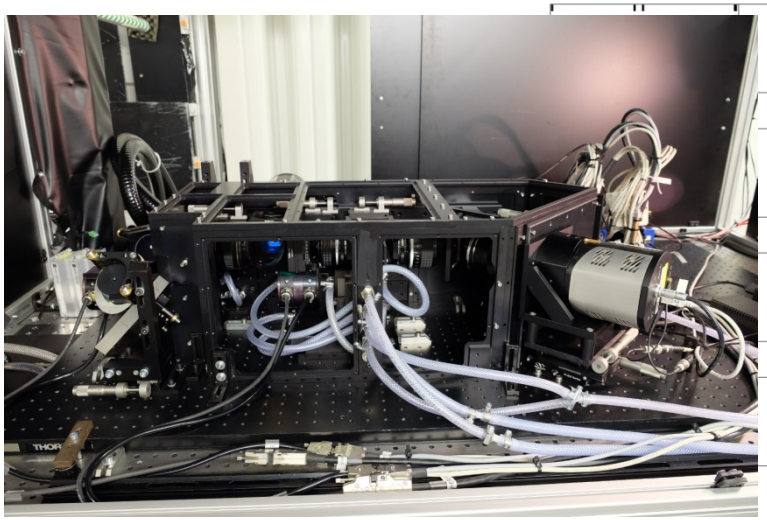
Chapter 7:
Gas-Phase Concentration measurement

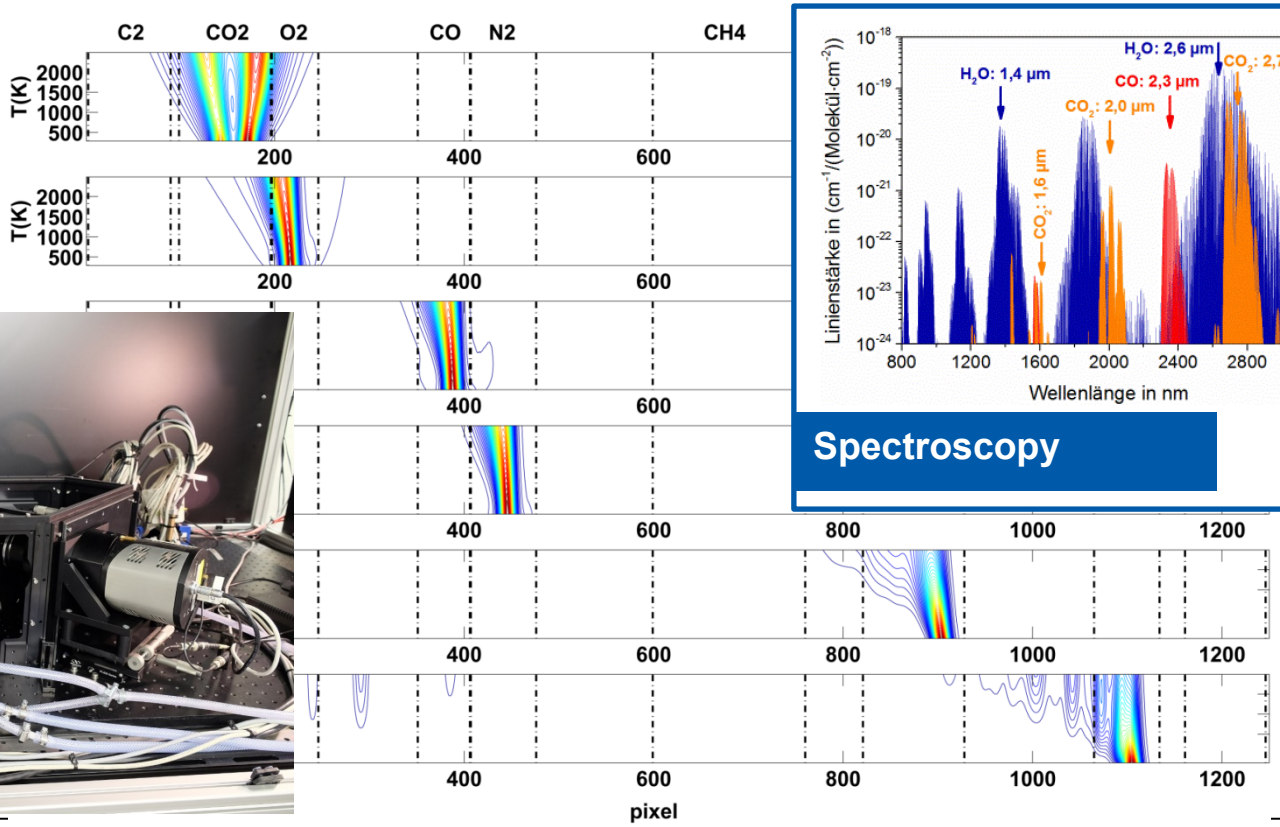
TU Darmstadt, Germany
Dept. of Mechanical Engineering
Institute for Reactive Flows and Diagnostics

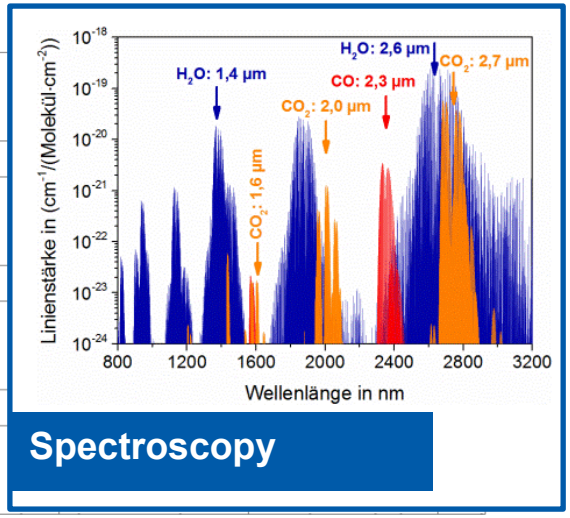
TECHNISCHE UNIVERSITÄT DARMSTADT

RSM Reaktive Strömungen + Messtechnik

A. Dreizler







Motivation for quantitative species concentration measurement

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- Quantitative concentration measurements are motivated by various scientific and technological issues
- Target species depends on the combustion process
  - Mixture fraction
  - Reaction progress and intermediate species concentration
  - Pollutants
  - …
- A quantitative species measurement in combustion application requires information of local gas temperature (density correction and method-related correction such as quenching correction in LIF)
  - Best option: measure simultaneously local temperature

Methods in the NIR/UV/VIS for temperature measurements via Boltzmann distribution

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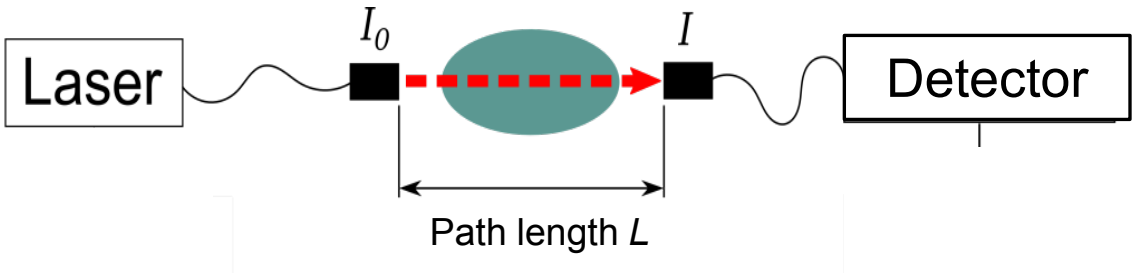
- Laser absorption spectroscopy (LAS)
- Laser-induced fluorescence (LIF)
- Raman spectroscopy (RS)

Laser absorption spectroscopy (1)

- Experimental setup



- Deduce number densities from Beer-Lambert's law (shown in its simplest form)

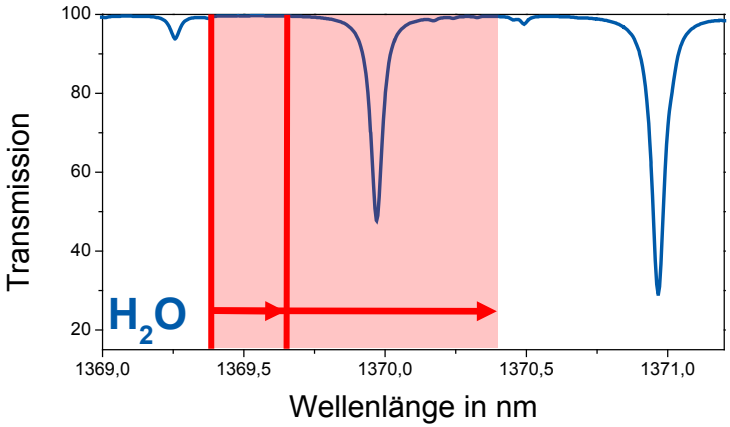
$$I(L) = I_0 \exp\left(-L \cdot N_J \cdot \sigma_{j \leftarrow i}\right) \Leftrightarrow N_J = \frac{\ln\left(I(L)/I_0\right)}{L \cdot \sigma_{j \leftarrow i}}$$

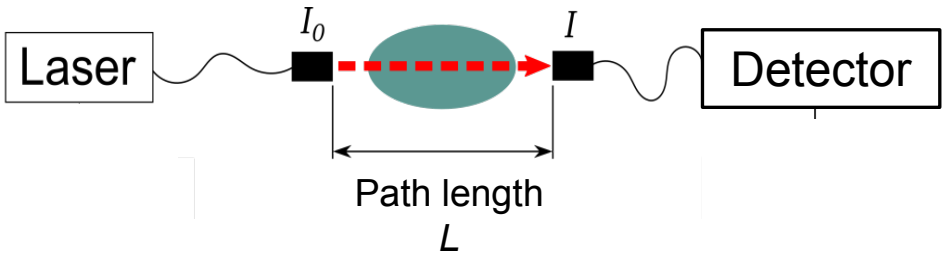
Calibration free (once the path length and absorption cross-section is known)

Line-of-sight: no resolution along laser beam path

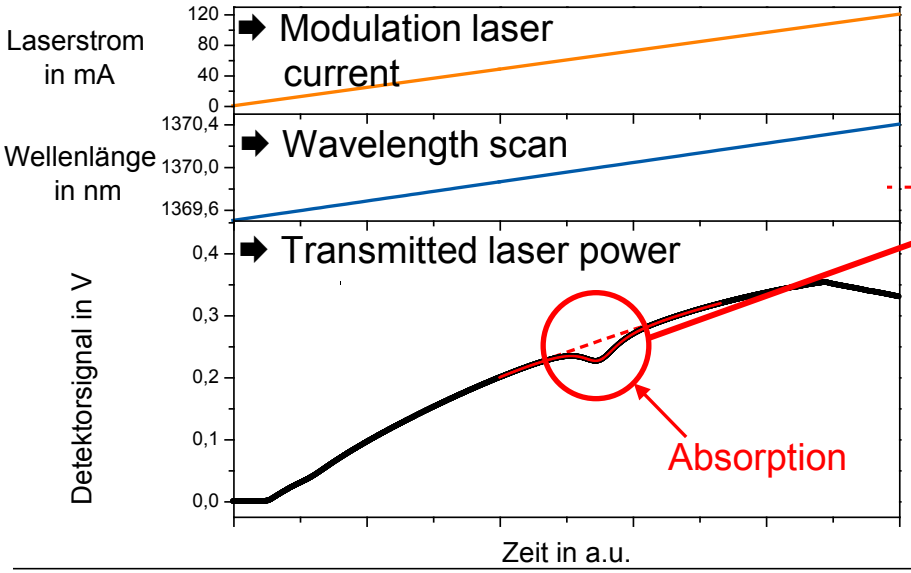
→ restrictions for application in turbulent flames

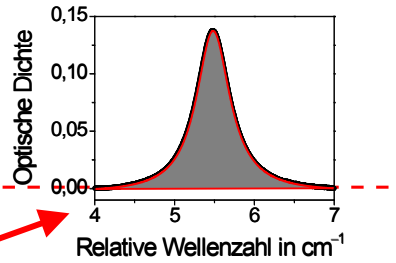
Tuneable diode laser absorption spectroscopy
TDLAS





Lambert-Beer-law





Ideal gas law

⬇

species concentration

$$c = \frac{k_B \cdot T}{S(T) \cdot L \cdot p} \int \ln\left(\frac{I_0(\nu)}{I(\nu)}\right) \frac{d\nu}{dt}\, dt$$

Laser Induced fluorescence: Principle

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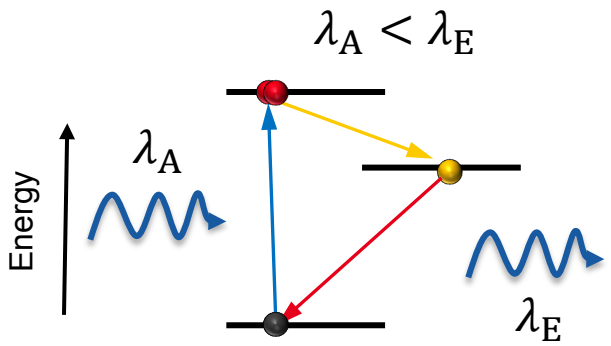
Step 1: Absorption

- Electronic excitation of molecules by laser radiation
- Wavelength λ_A



Step 2: Spontaneous emission (fluorescence)

- Spectrally red-shifted $\lambda_A < \lambda_E$
- Upper state lifetime few ns
- Measure of local number density

- Linear LIF regime

$$I_{LIF}(x) = N_1(x)\sigma(\nu)I_{laser}(x)\frac{\tau_{tot}}{\tau_{sp}}U\frac{\Omega}{4\pi}\varepsilon\eta$$

RSM Reaktive Strömungen + Messtechnik

Laser Induced fluorescence: Experimental setup

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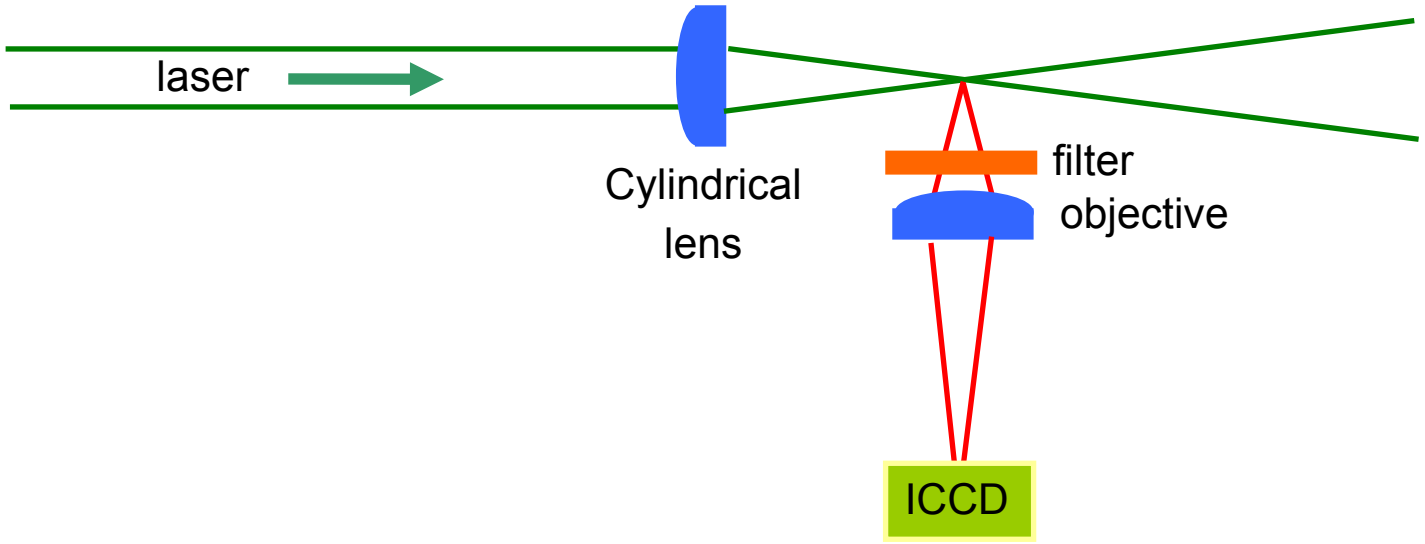
- Experimental setup



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Laser Induced fluorescence: pros and cons

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$$I_{LIF}(x) = N_i(x)\sigma(\nu)I_{laser}(x)\frac{\tau_{tot}}{\tau_{sp}}U\frac{\Omega}{4\pi}\varepsilon\eta$$

- Good spatial resolution (90° detection angle)
- Sensitive
- Calibration required to determine $U\frac{\Omega}{4\pi}\varepsilon\eta$
- Total lifetime τ_{tot} needed but often not known!

$$\tau_{tot} = \frac{1}{A+P+Q}$$

A: Einstein A-coefficient, molecular property, often known

P: Predissociation rate, molecular property, often known

Q: Quenching rate, depends on gas matrix, pressure, temperature → PROBLEM

Total lifetime τ_{tot} makes quantitative LIF challenging!

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How to make LIF quantitative – options

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1. Quantification of τ_{tot} : Measure τ_{tot} = fct(T, species),
   once τ_{tot}(T, species) is known measure LIF simultaneously with T and species (via Raman/Rayleigh)
2. Calibration: determine $C = C(T)$ in $I_{LIF}(x) = C(T)\left[N_1(x)\right]$
   →Example CO-LIF in application example flame-wall interaction
3. Saturated LIF: does not really work, not detailed here
4. Combine 1D-LIF with absorption spectroscopy (see CST 158, 2000, Pixner et al.)

$$N_1(x) = -\frac{1}{\sigma}\cdot\frac{(T-1)\dfrac{dV(x)}{dx}}{(T-1)V(x)+1}$$

$$V(x) = \frac{\int_0^x F(x')dx'}{\int_0^L F(x')dx'} = \frac{\exp\left(-\sigma\int_0^x N_1(x')dx'\right)-1}{\exp\left(-\sigma\int_0^L N_1(x')dx'\right)-1}$$

$$T = \frac{I(L)}{I(0)} = \exp\left(-\sigma\int_0^L N_1(x')dx'\right)$$

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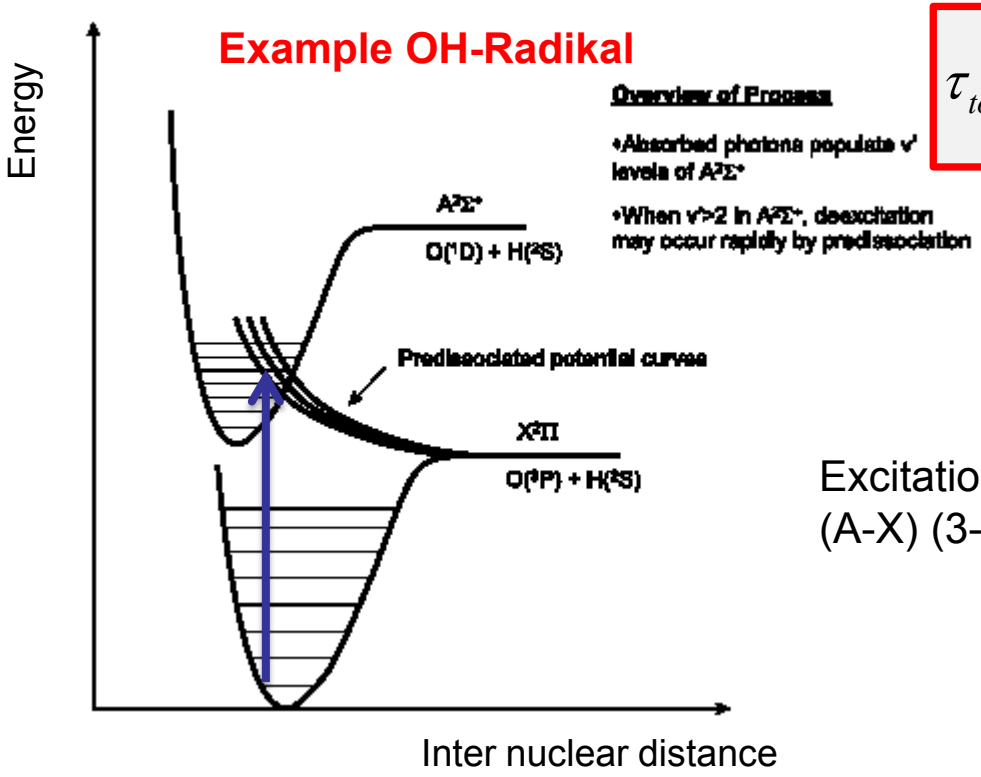
How to make LIF quantitative – options

5. Predissociative LIF: Independent of Q; low SNR, works for few molecules at low pressure

Example OH-Radikal

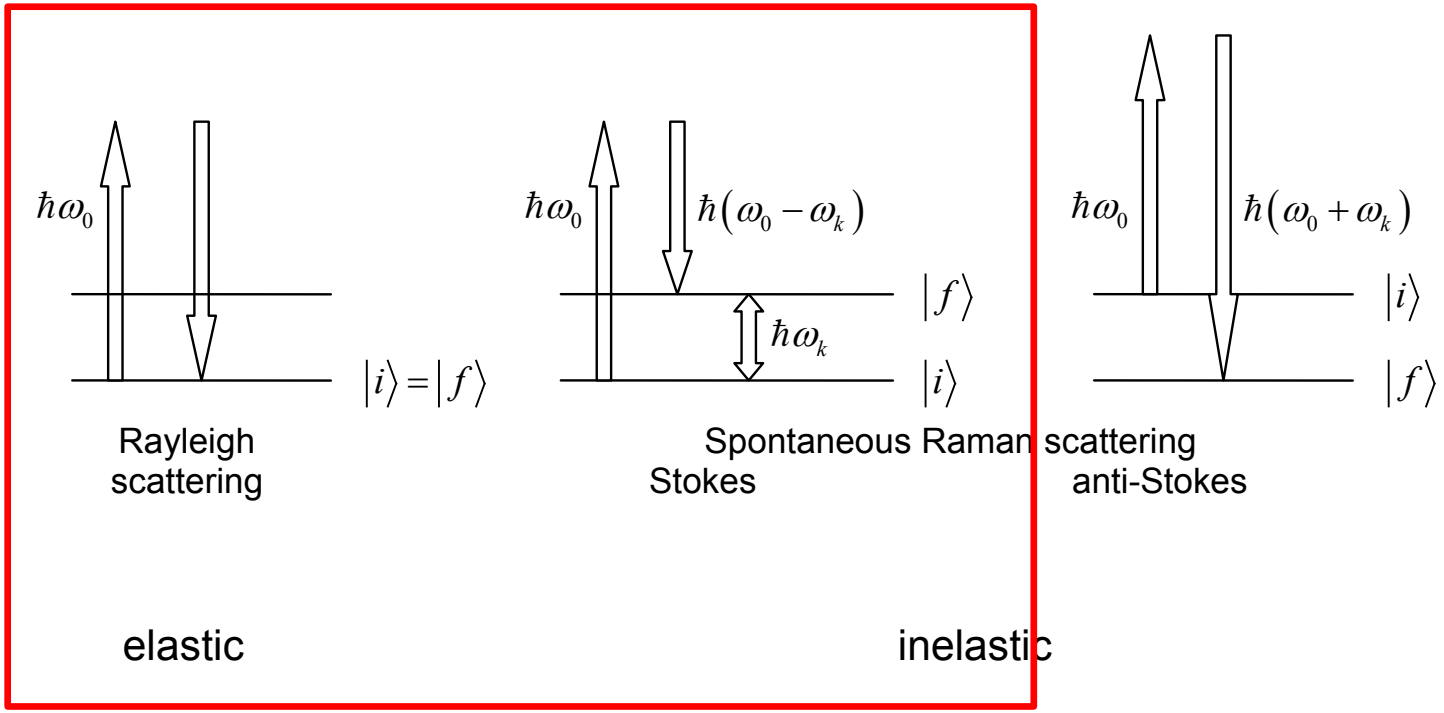


$$\tau_{tot} = \frac{1}{A+P+Q}, \text{ for } P >> Q : \tau_{tot} = \frac{1}{A+P}$$

Excitation at 248 nm by KrF-Excimer Laser (A-X) (3-0)-band

Raman spectroscopy

- Elastic and inelastic light scattering of photons off molecules



Combined Raman/Rayleigh spectroscopy

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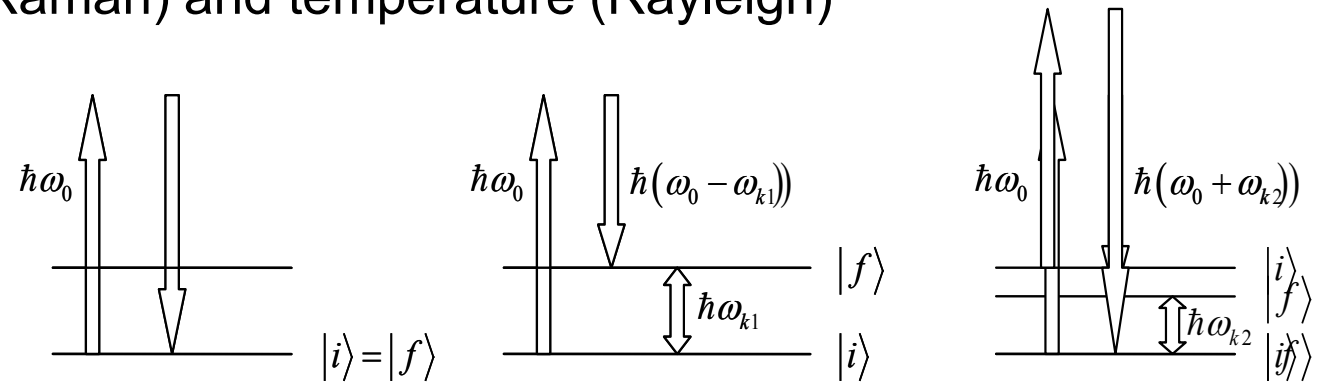
- Multi-scalar method: instantaneous measurement of main species (Raman) and temperature (Rayleigh)



- Spectral dispersion and simultaneous meas. of: CO_2, O_2, CO, N_2, CH_4, H_2O, H_2, equivalence ratio (phi), Temp.
- **Challenges:**
  - Low Raman scattering cross-sections and single-shot requirement
  - Data evaluation of noisy data
  - 1D application, high spatial resolution

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Raman spectroscopy: selection rules and spectra

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- Selection rules

$\Delta J = 0, \pm 2$

$\Delta J = 0 \rightarrow$ Q-branch

$\Delta J = +2 \rightarrow$ O-branch

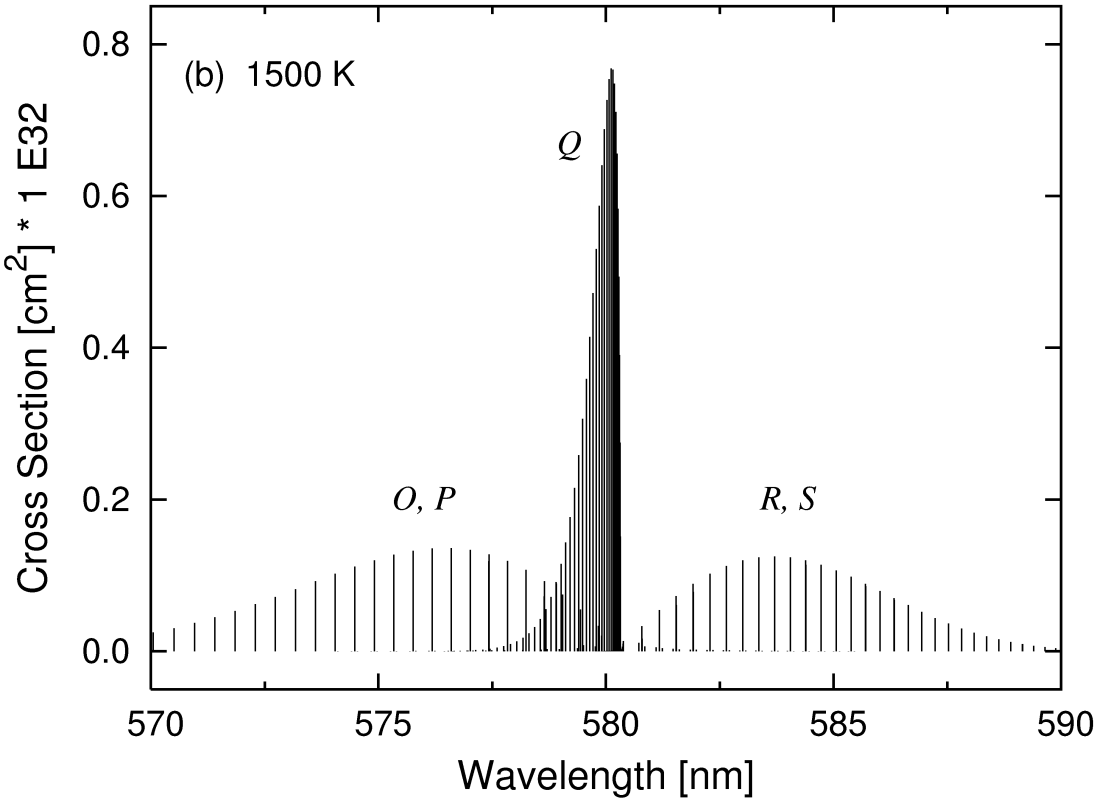
$\Delta J = -2 \rightarrow S$-branch

Oxygen molecule O_2, T = 1500 K

Simulated “stick spectrum” – infinite resolution

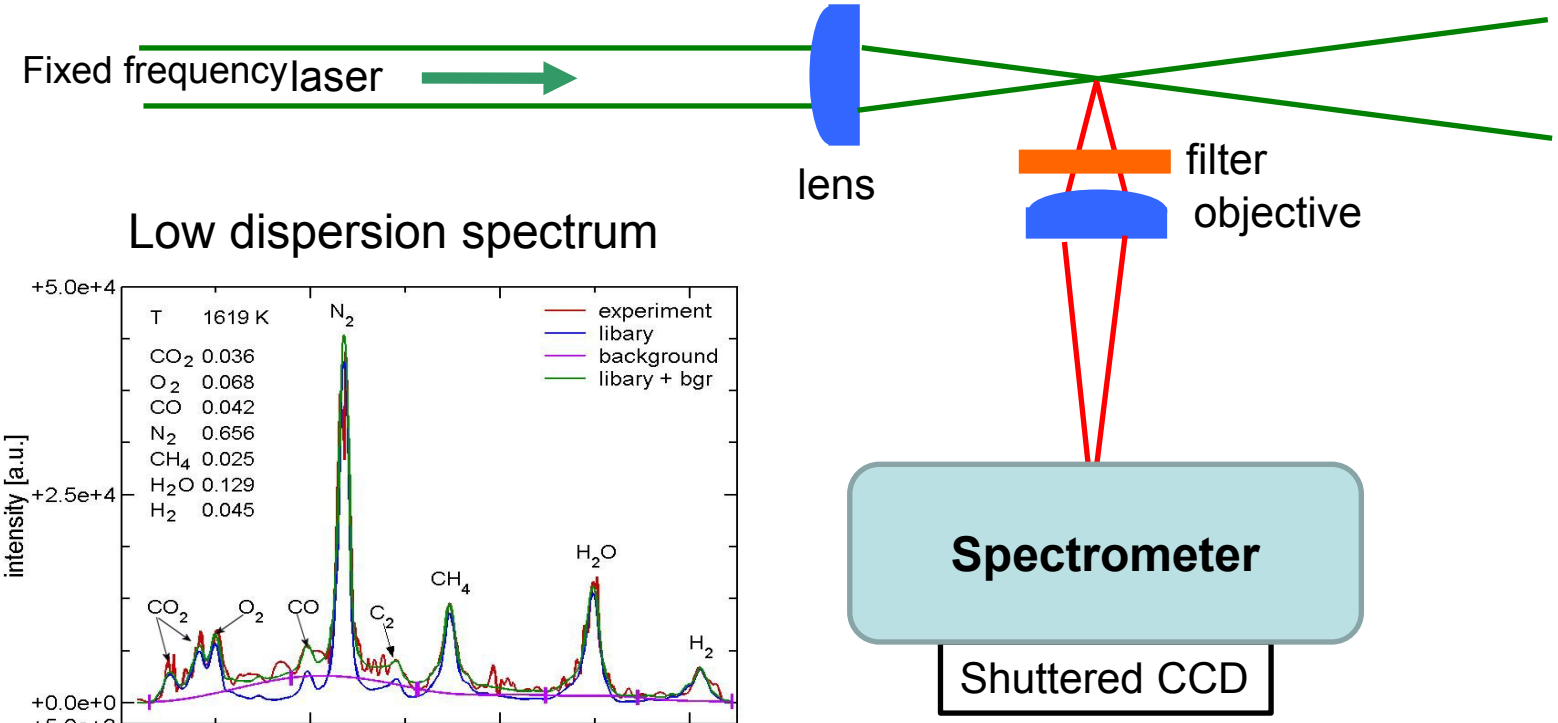
Ro-vibronic Stokes Raman

Exception: very weak R and P-lines

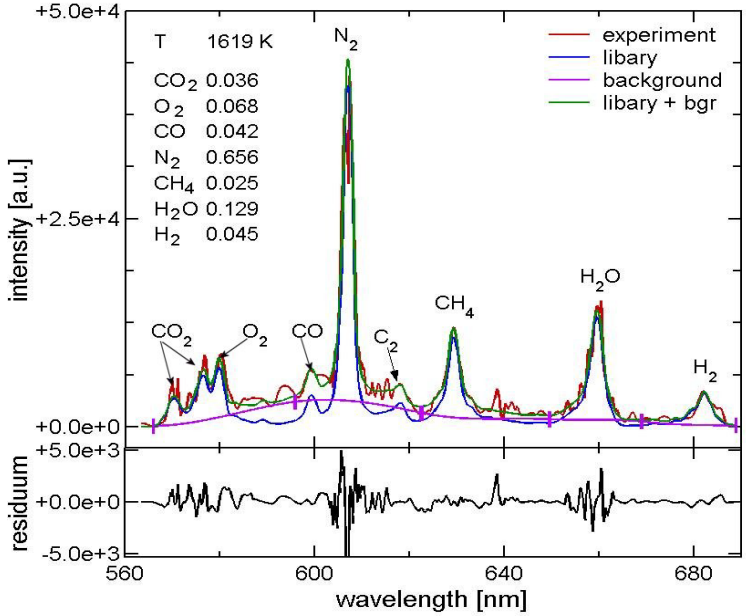


Raman spectroscopy: setup

- Experimental setup



Low dispersion spectrum



1D Raman/Rayleigh: spectrometer

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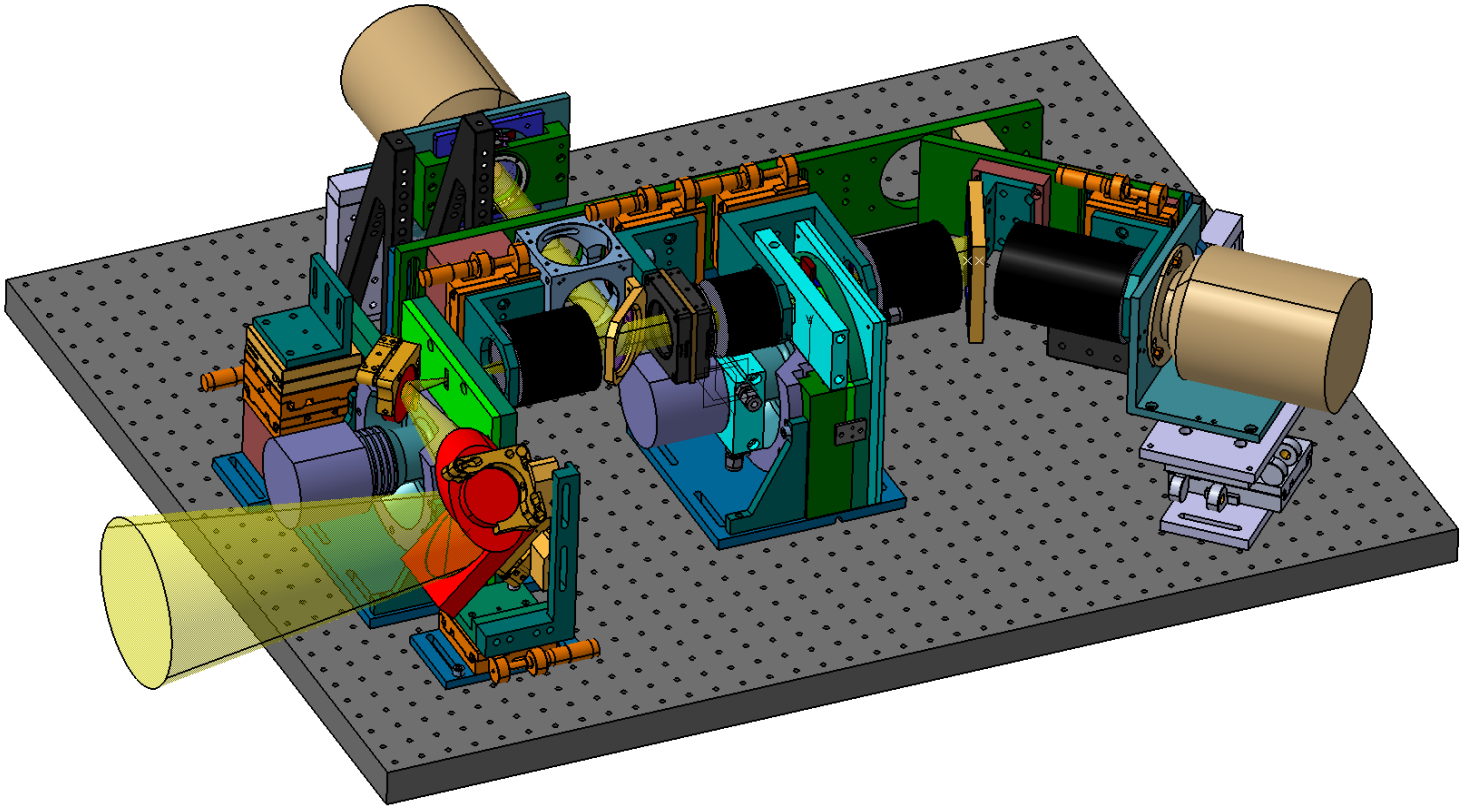
- New TU Darmstadt design



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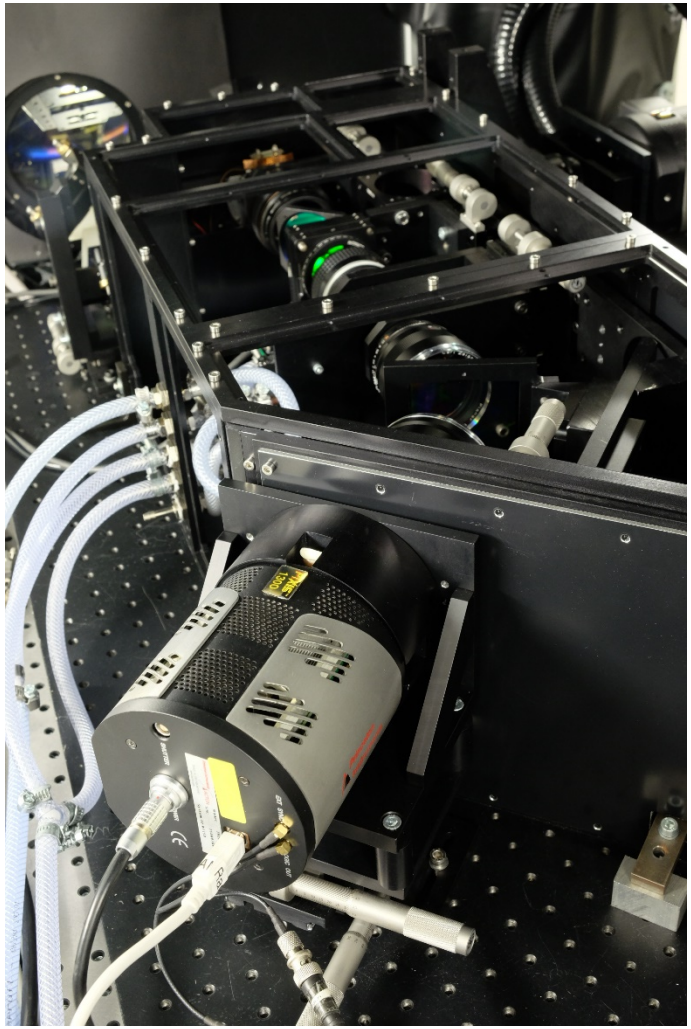
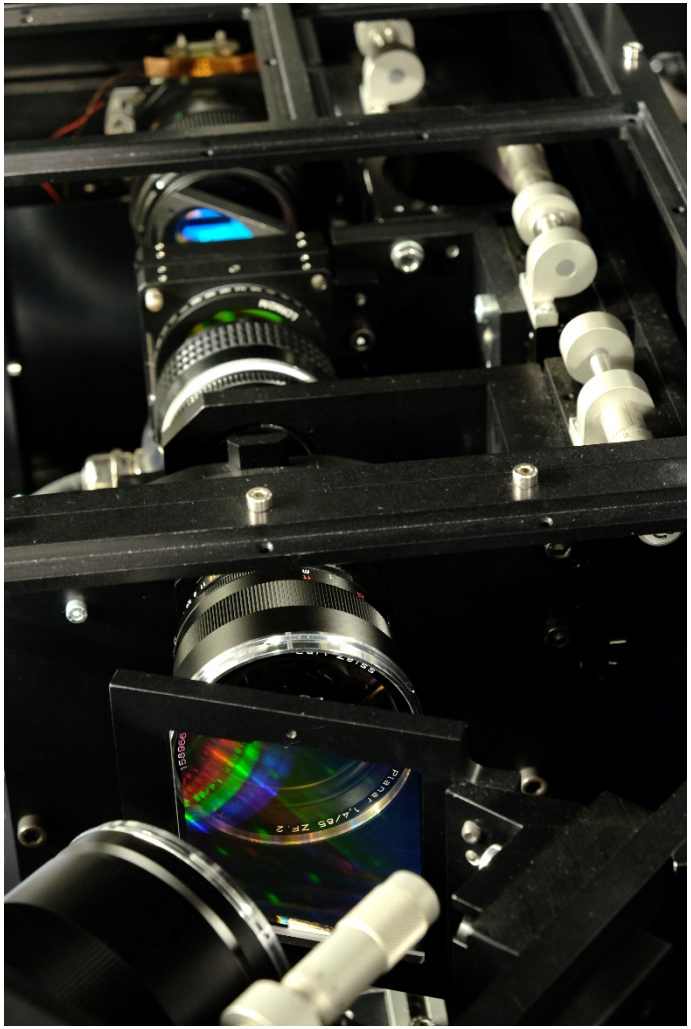
1D Raman/Rayleigh: spectrometer





1D Raman/Rayleigh spectroscopy: iterative post-processing procedure

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- **Raman (inelastic) scattering → concentrations $N_i(r)$**

$$S_{ram,i}\left(\vec{r}\right) \propto \sigma_{ram,i}\left(T(\vec{r})\right)\ I_{Laser}\ \ N_i(\vec{r})$$

- **Rayleigh (elastic) scattering → temperature T(r)**

$$S_{ray}\left(\vec{r}\right) \propto \sigma_{ray}\left(N_i(\vec{r})\right) I_{Laser} \sum N_i\left(\vec{r}\right)$$

$$\sigma_{ray} = \sum_i \left(\frac{N_i\left(\vec{r}\right)}{\sum_j N_j\left(\vec{r}\right)} \right) \sigma_{ray,i} \xrightarrow{\text{Ideal gas law}} T\left(\vec{r}\right) \propto \frac{1}{\sum N_i\left(\vec{r}\right)}$$

→ **Determination of N_i, T by iterative procedure: Need $\sigma_{ram,i}$ of each species *i***

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Different options for data evaluation

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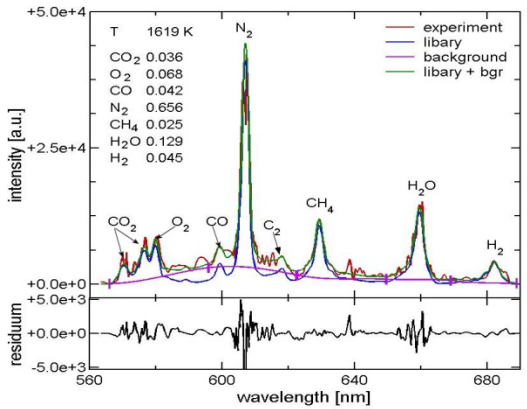
- Spectral fit



- Matrix inversion (MI) method

$$\vec{S} = \underline{\underline{M}} \bullet \vec{N}$$

$$\Rightarrow \vec{N} = \underline{\underline{M}}^{-1} \bullet \vec{S}$$

Combining the strength of both
→**The Hybrid MI-method**

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A Hybrid Method for Data Evaluation in 1D Raman Spectroscopy

F. Fuest[1], R.S. Barlow[2], D. Geyer[3], F. Seffrin[1], A. Dreizler[1]

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TU Darmstadt, 64287 Darmstadt, Germany

[2] *Sandia National Laboratories, Livermore, CA 94551-0969, USA*

[3] *Hochschule Darmstadt - University of Applied Sciences, 64295 Darmstadt, Germany*

Supported by:
Deutsche Forschungsgemeinschaft (SFB 568 B1, EXC 259)
and the US Department of Energy, Office of Basic Energy Sciences

Motivation

- Spontaneous Raman scattering
  - important technique in combustion research
  - major species, scalar gradients, scalar dissipation
  - need best possible accuracy, precision, and spatial resolution
  - improvements in detection hardware and methods of analysis

- Two approaches to data analysis for hydrocarbon flames; both are complicated

- “Hybrid” method of Raman data analysis
  - combine strengths of methods used by Sandia and TU Darmstadt
  - reduce level of expertise needed to interpret Raman data

- Demonstrate using laminar flame measurements from Sandia system
  - Premixed CH_4/air flat flames
  - Laminar H_2 jet flame (no hc fluorescence interference)

Matrix Inversion (Sandia)

- On-chip binning of Raman bands to reduce camera readout noise
- Matrix equation relating signals and sources

$$S_{CO2} = C_{1,1}(T)xN_{CO2} + C_{1,2}(T)xN_{O2} + C_{1,5}(T)xN_{CH4} + C_{1,7}(T)xN_{H2} + C_{1,9}(T)xC2 + C_{1,10}(T)xBck$$

Raman — Raman crosstalk — fluorescence — background

$$\begin{bmatrix} S_{CO2} \\ S_{O2} \\ S_{CO} \\ S_{N2} \\ S_{CH4} \\ S_{H2O} \\ S_{H2} \\ S_{CO\text{-}LIF} \\ F560 \\ b3 \end{bmatrix} = \begin{bmatrix} C_{11}(T) & & & & & & & & & \\ & \ddots & & & & & & & & \\ & & \ddots & & & & & & & \\ & & & \ddots & & & & & & \\ & & & & \ddots & & & & & \\ & & & & & \ddots & & & & \\ & & & & & & \ddots & & & \\ & & & & & & & \ddots & & \\ & & & & & & & & \ddots & \\ & & & & & & & & & \ddots \end{bmatrix} \begin{bmatrix} N_{CO2} \\ N_{O2} \\ N_{CO} \\ N_{N2} \\ N_{CH4} \\ N_{H2O} \\ N_{H2} \\ N_{CO\text{-}LIF} \\ \text{“C2”} \\ Bck \end{bmatrix}$$

- Extensive calibrations to determine temperature dependence of matrix elements for Raman response and crosstalk (represented as polynomials)
- Solve inverse problem to get species concentrations and temperature
- Iterate on Rayleigh temperature (1K conversion, 3-4 iterations)

Spectral Fitting (TU Darmstadt)

- Individual rovibrational Raman transitions calculated for each species, based on Placzek´s theory of polarizability (TUD Ramses code)

- Each Raman transition convolved with experimentally determined apparatus function, then all convolved Raman transitions superposed
  - Rayleigh scattering image → apparatus function in this work
  - Raman bands broaden with increasing temperature due to the population of higher quantum states
  - Spectral library composed of temperature-dependent Raman bands

- The spectral library for each molecule is calibrated to an experimental spectrum measured in a gas sample with known mole fraction and temperature.

- Details of fitting procedure (Dirk Geyer thesis)

Pro's and Con's

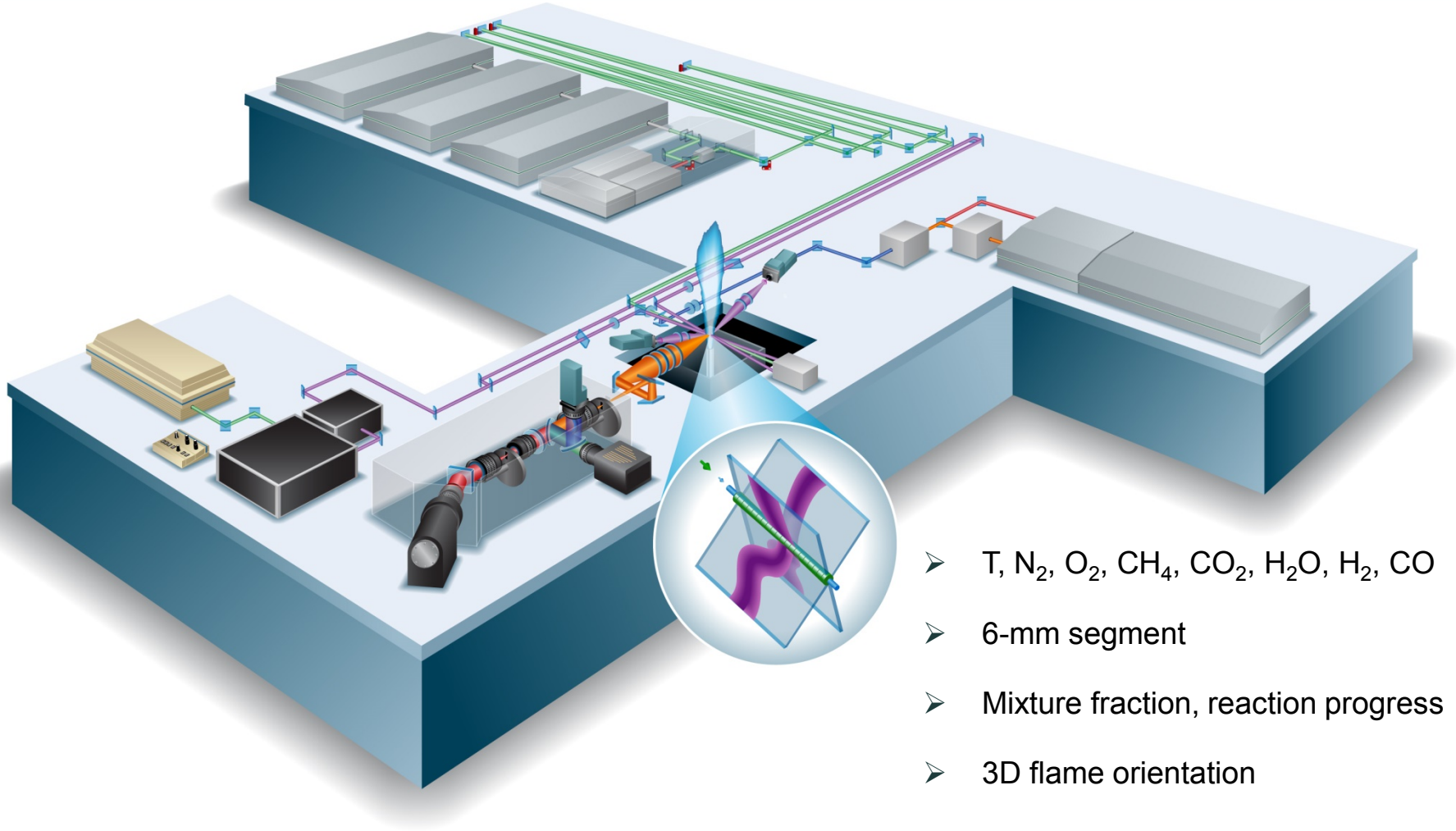
Matrix Inversion (old version)

- Pro's
  - Lower noise
  - Faster acquisition & processing
- Con's
  - Extensive calibrations required
  - Cannot calibrate accurately at some conditions
  - Spectral information lost
  - Impractical to account for beam steering or spatial dependence of response function

Spectral Fitting

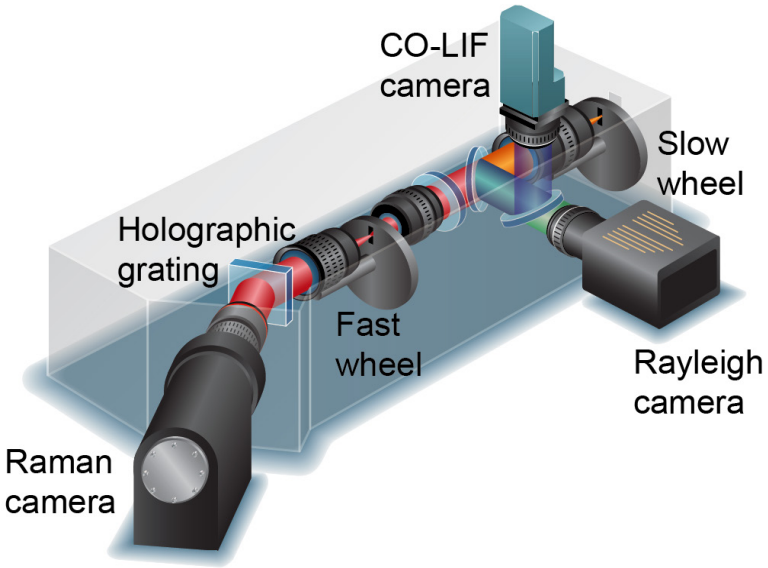
- Pro's
  - Based on quantum mechanical theory
  - One calibration per species
  - Beam steering handle automatically
  - Background corrected more rigorous
- Con's
  - Higher readout noise
  - Slower data acquisition rate
  - Significant time/effort in fitting

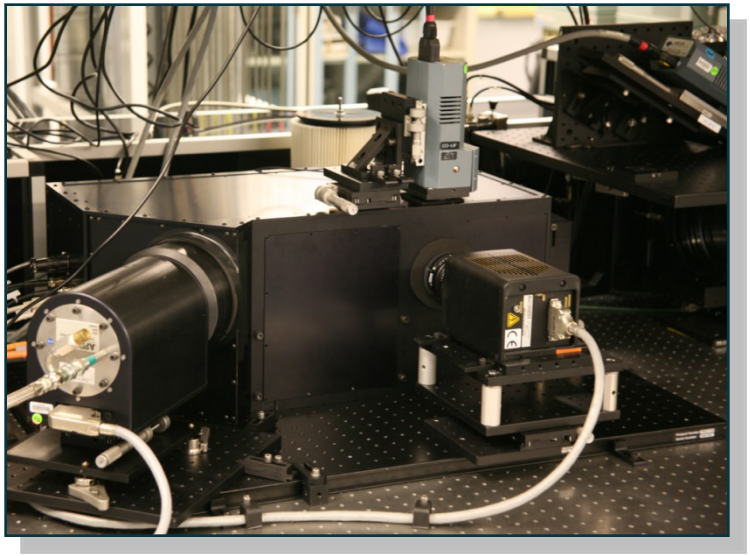
Turbulent Combustion Laboratory: Raman/Rayleigh/CO-LIF & Crossed OH PLIF

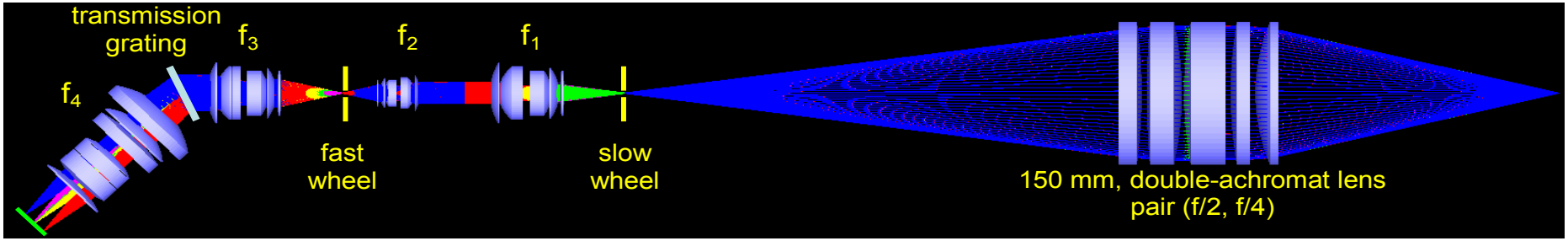


- T, N_2, O_2, CH_4, CO_2, H_2O, H_2, CO
- 6-mm segment
- Mixture fraction, reaction progress
- 3D flame orientation
- 1D, 3D scalar gradients, dissipation

Detection System

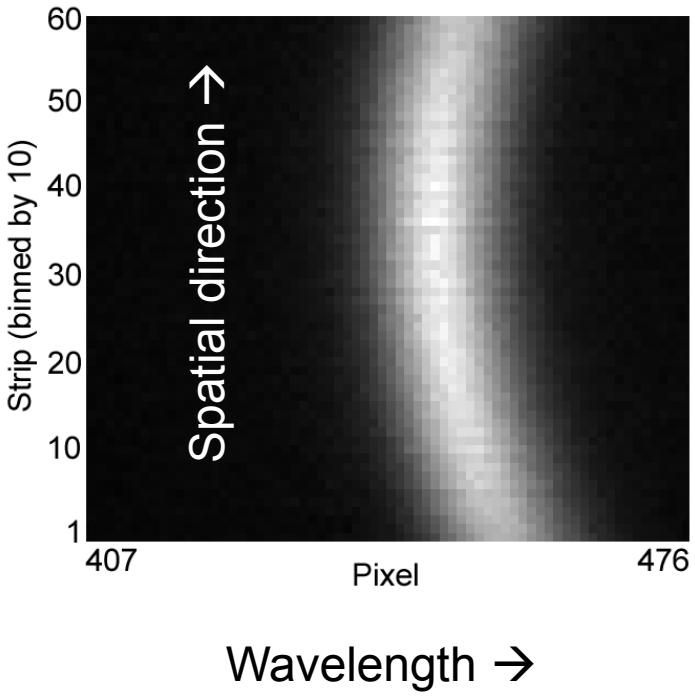






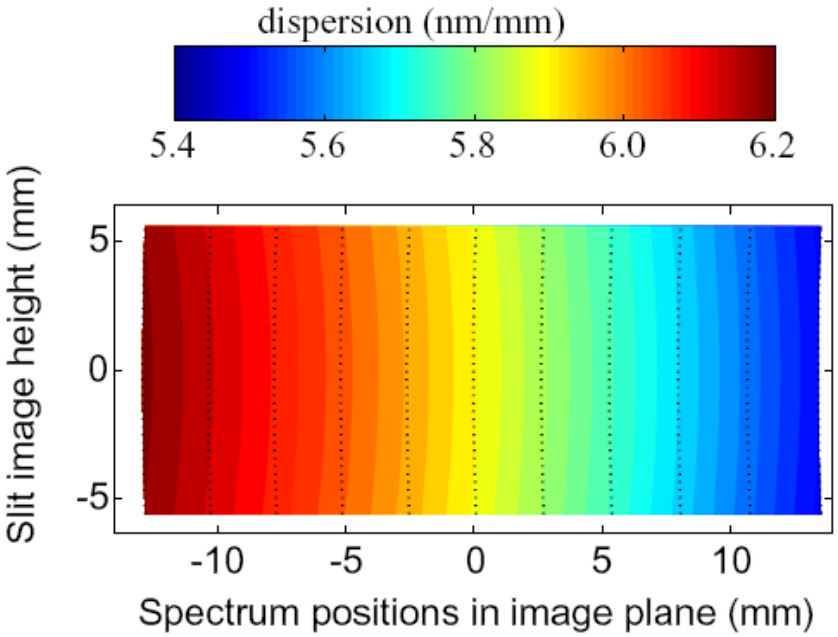
- LSF 40-60 μm
- Transmission grating
- Mechanical gate: 3.9 μs gate (FWHM)
- 103 μm data spacing

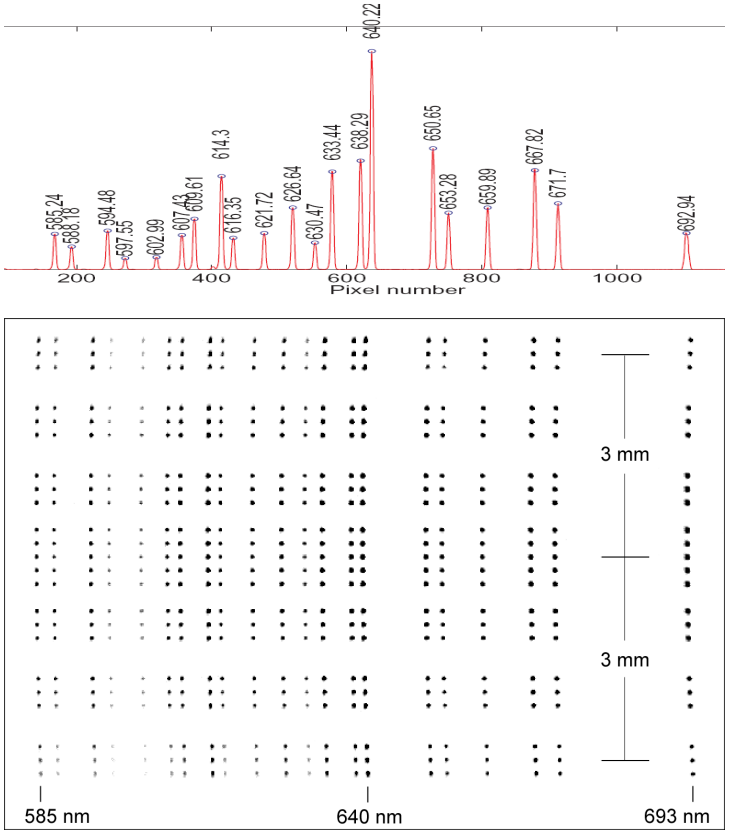
Optical Bowing Effect



- Image of N_2 Raman scattering in air
- Low f-number spectrograph
  - bowed image of slit
  - Jun Zhao, Appl. Spectr. 57, 11 (2003) 1368-1375
- Calculated (Zemax) and measured
  - Map CCD for wavelength at each pixel
- Must account for this optical effect

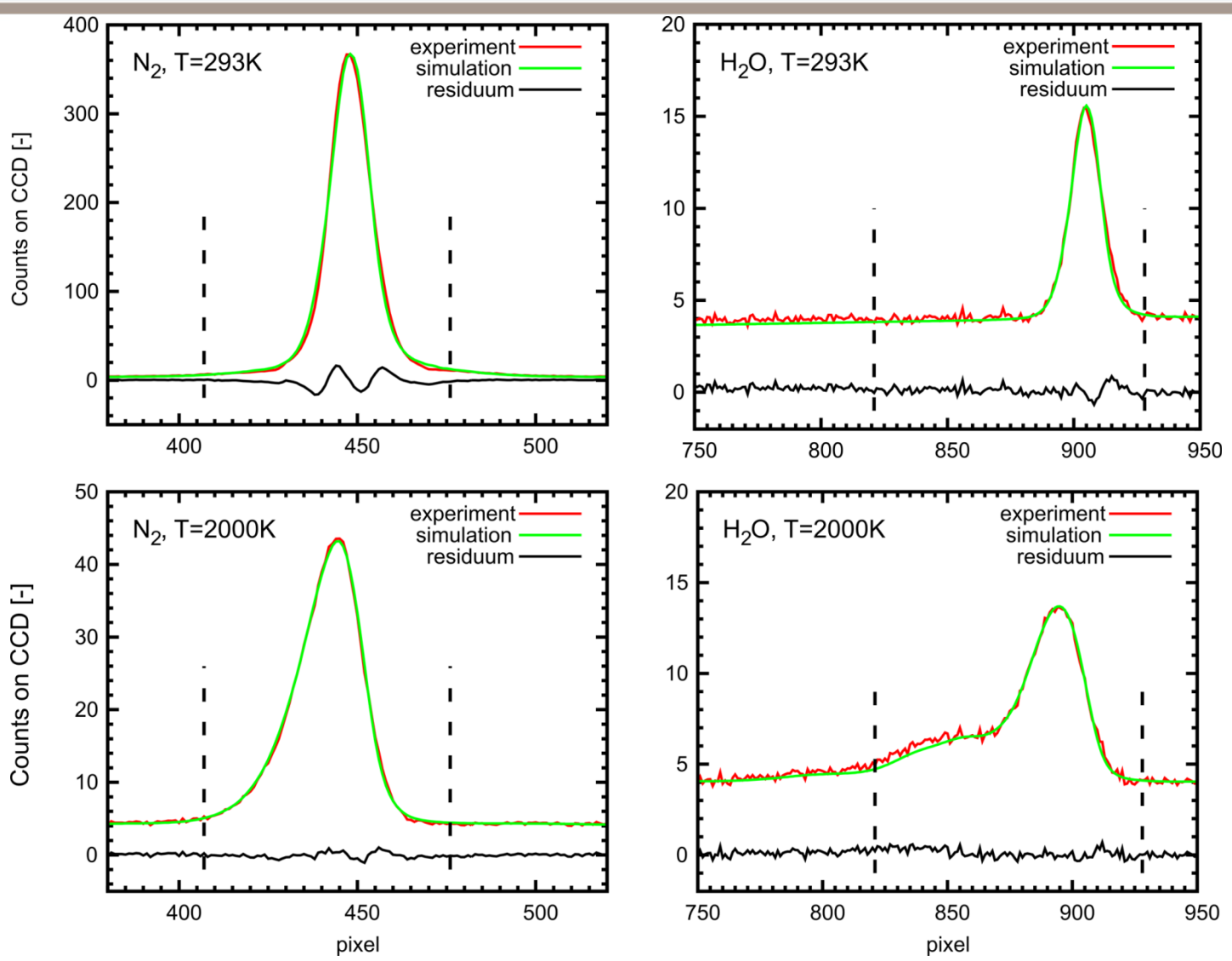
Spectrometer Characteristics



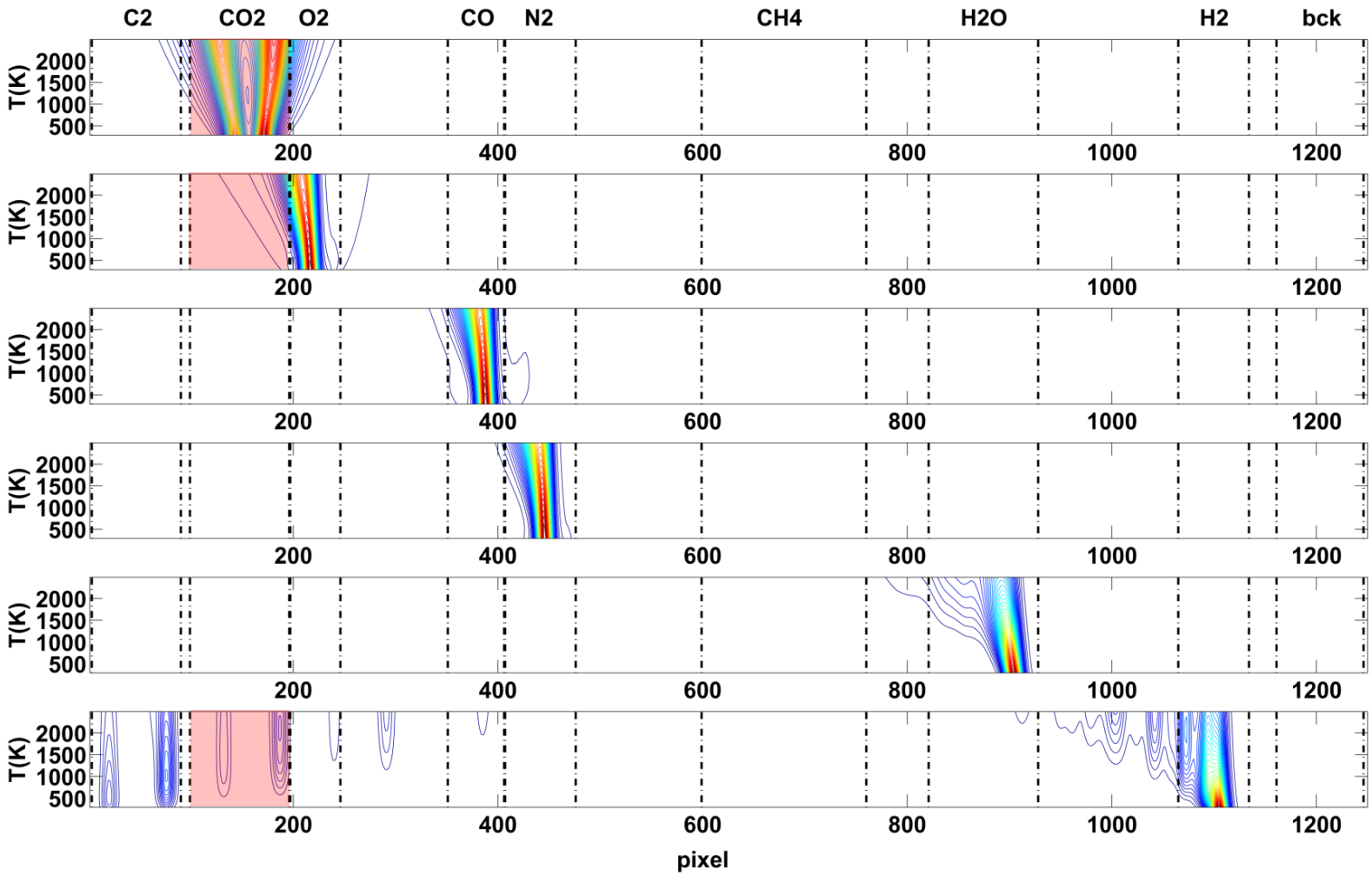


- Calculated (Zemax) dispersion is not linear across the image plane
- Spectral/spatial calibration using neon lamp and target with 50-μm holes on 200-μm centers

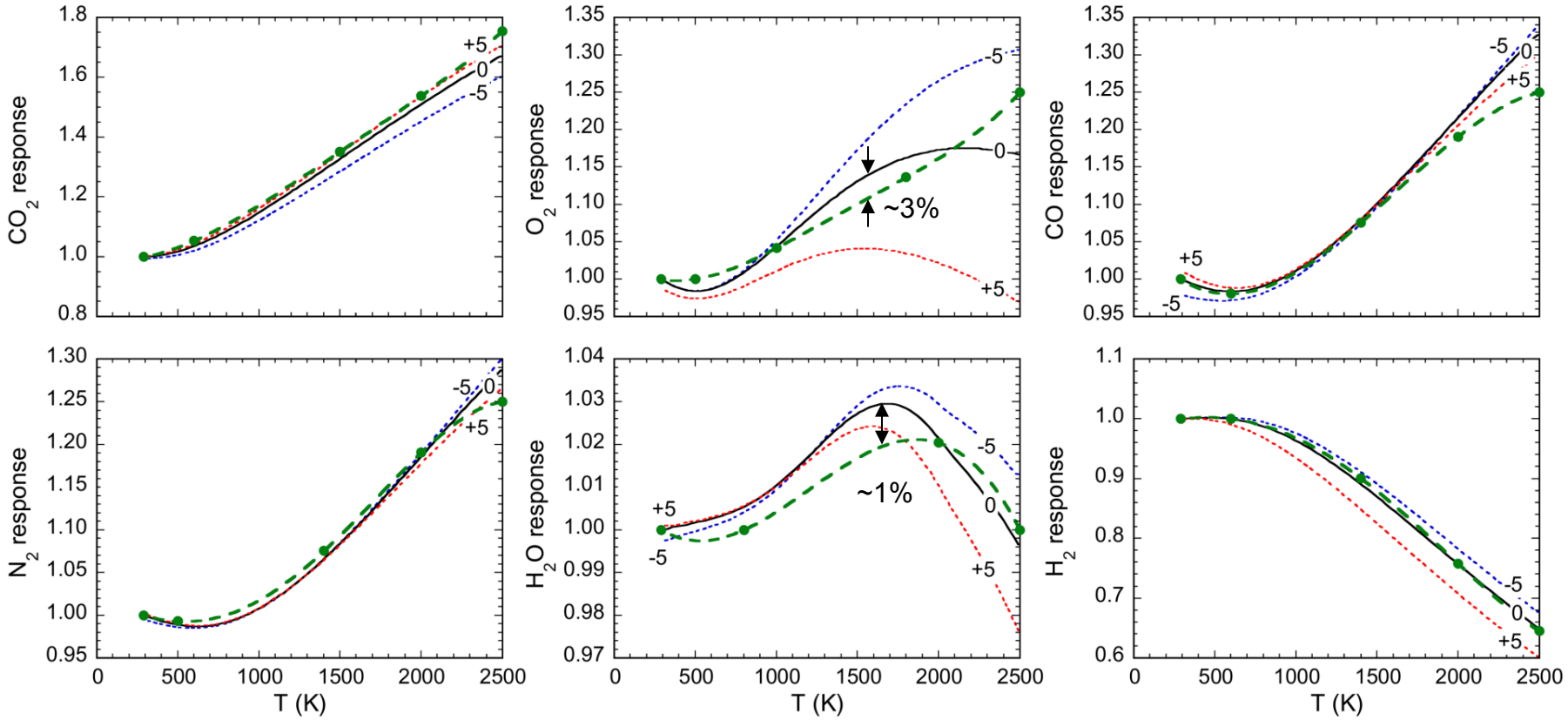
Spectral Library vs. Measurement



Calculated Spectral Libraries (Ramses code)

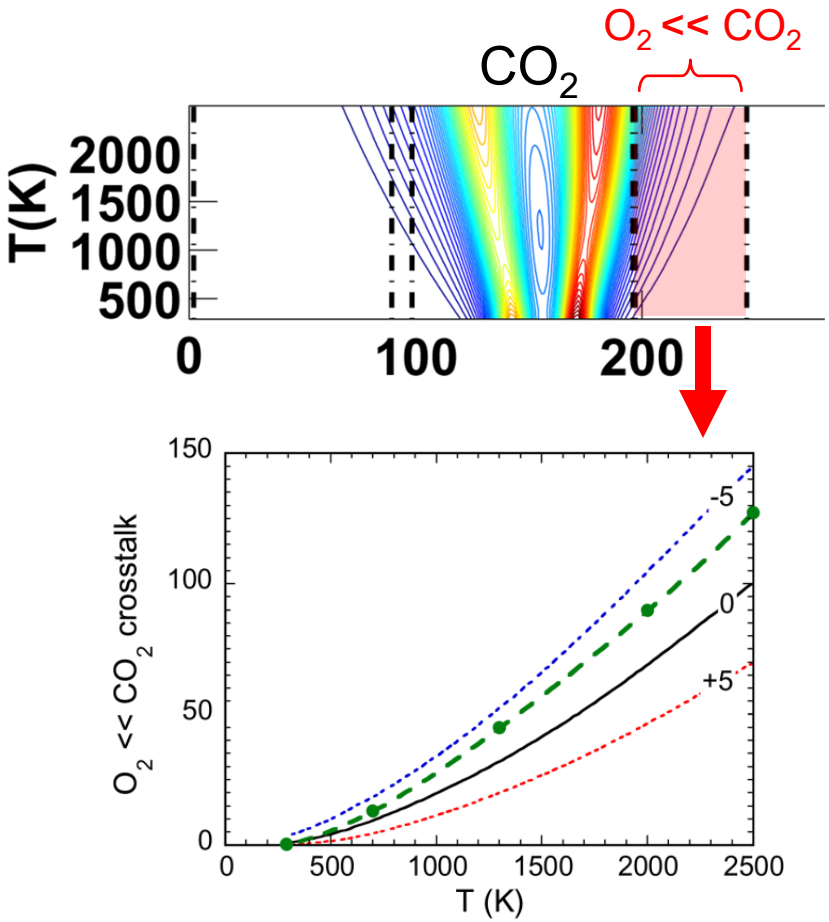


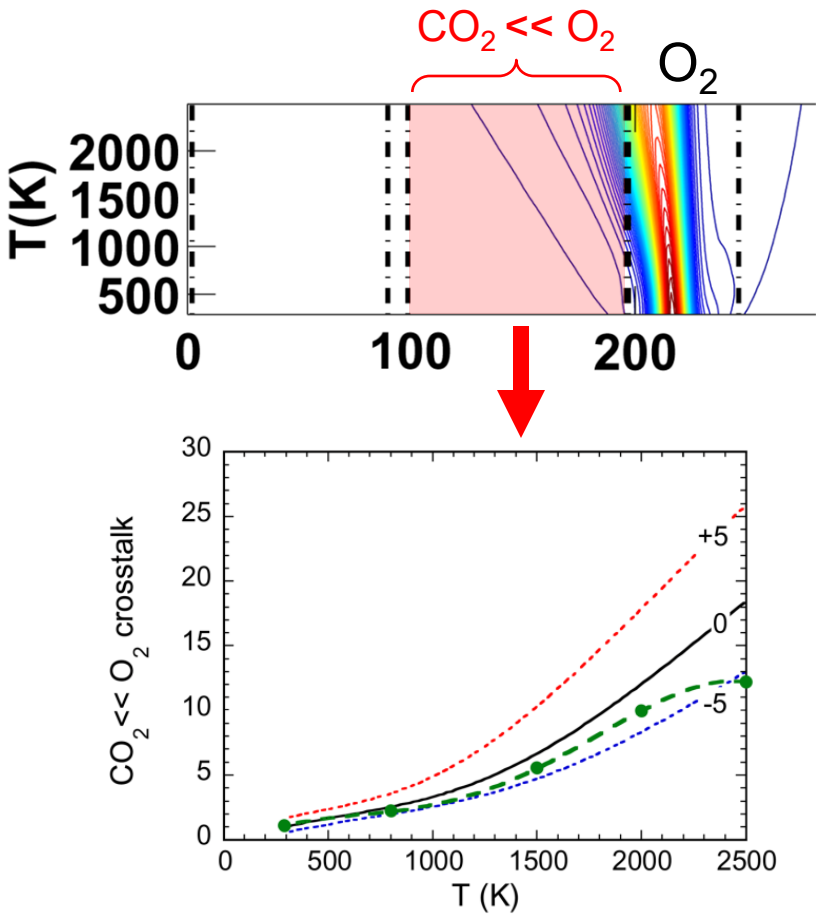
Major Species Response Curves



- Good agreement, except for O_2 curve shape at high T
- O_2 response sensitive to bowing effect and beam steering

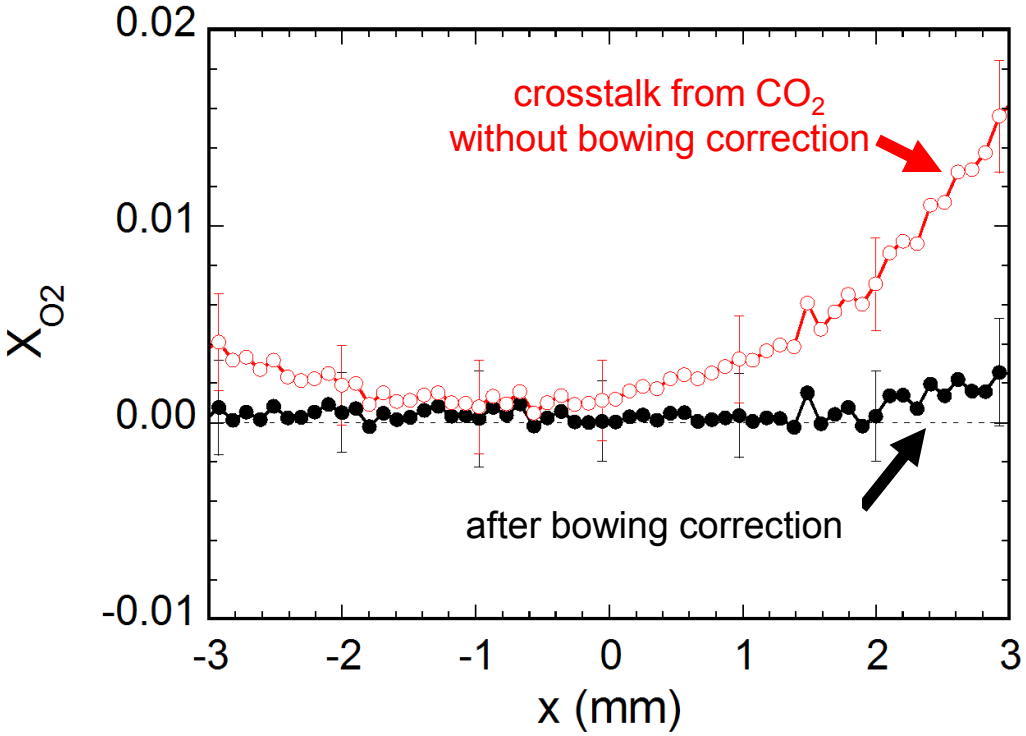
Crosstalk between CO_2 and O_2





- Greater uncertainty in calibration polynomials
- Sensitive to bowing effect and beam steering

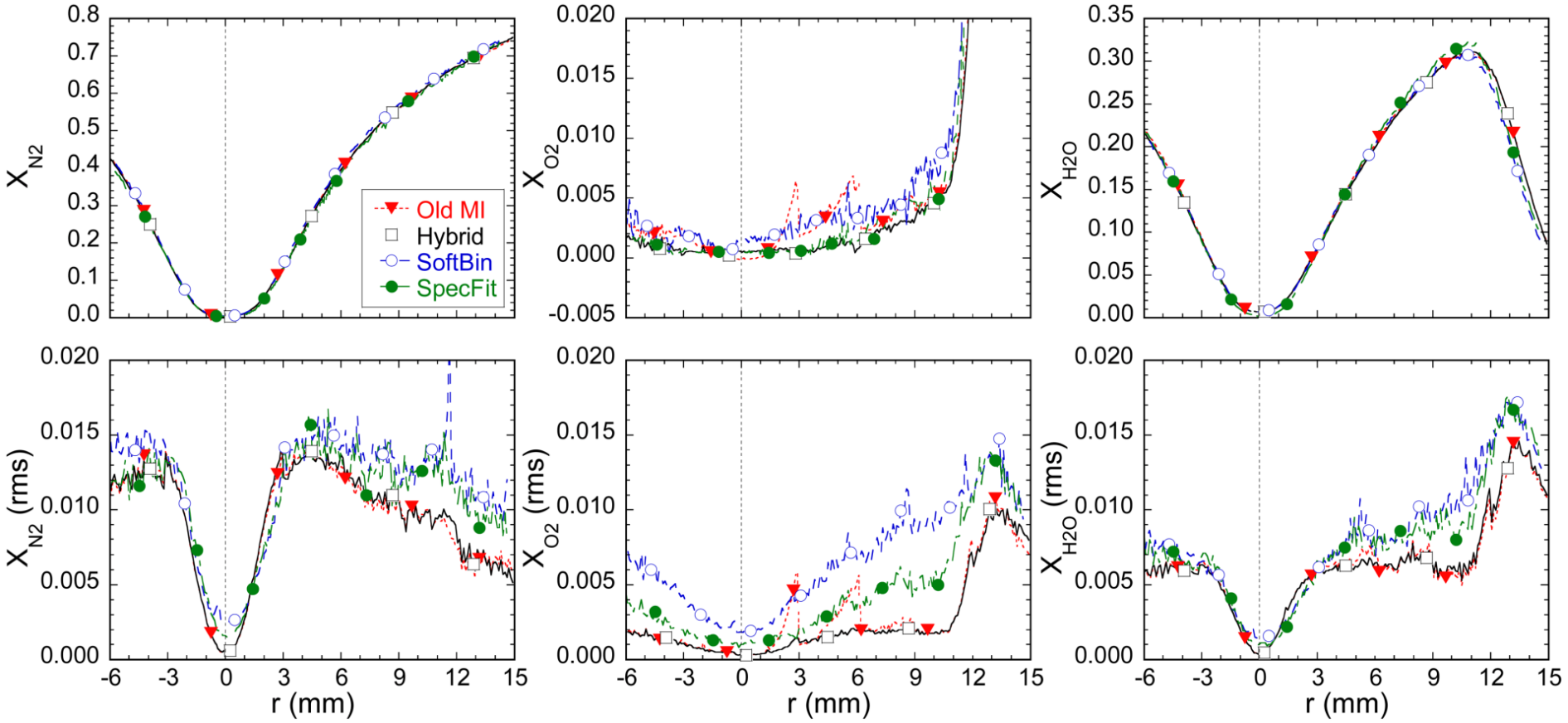
Effects of Image Bowing on O_2 Errors



premixed CH_4/air
"flat" calibration flame

- O_2 mole fraction should be zero in the rich flame products (ϕ=1.3)
- Bowing effect leads to error of X_{O2} ~ 1.6% due to uncorrected CO_2 crosstalk

Comparison for Laminar H_2 Jet Flame



- Close agreement on mean values from hybrid-MI and spectral fitting
- Hybrid method yields better precision (on chip binning)
- Spectral fitting yields lower noise than MI with software binning

Conclusions

- Hybrid method of Raman data analysis has been developed
  - Calculated Raman libraries are integrated to determine temperature-dependent terms for matrix inversion
  - Response and cross talk for N_2, O_2, H_2, CO, CO_2, H_2O
- Combines advantages from both previous methods
  - Low noise from on-chip binning
  - Fast data acquisition and processing
  - Temperature dependence based on QM theory
  - Automatic correction for image bowing and beam steering
- Relatively easy to adapt to other Raman/Rayleigh systems

Application example

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- Thermo-chemical state in swirling premixed flame: PCI 32 2009, Gregor et al.

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Thermo-chemical state in swirling premixed flame

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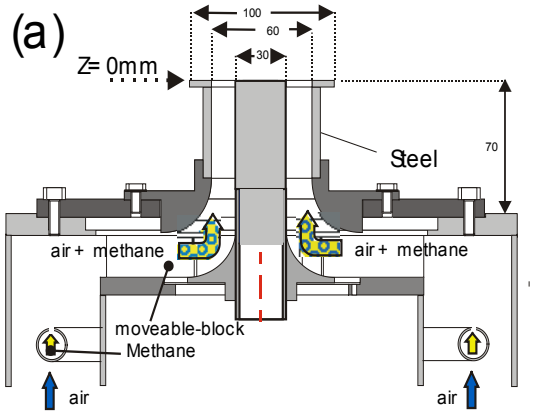
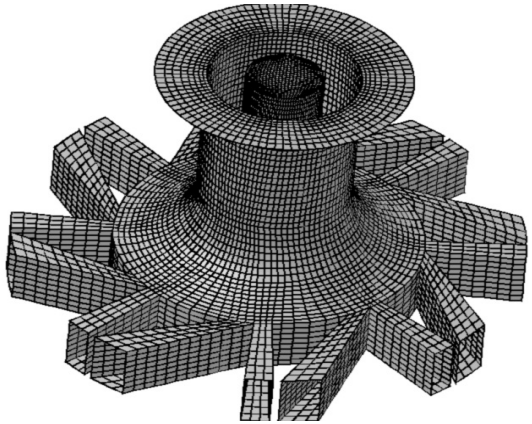
- Burner





- Operational conditions

		PSF-30	*PSF-90*	*PSF-150*
$S_{0,th}$	[-]	0.75	0.75	0.75
P	[kW]	30	90	150
ϕ	[-]	0.833	0.833	1.0
$Re_{tot.}$	[-]	10000	29900	42300

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Measurement locations

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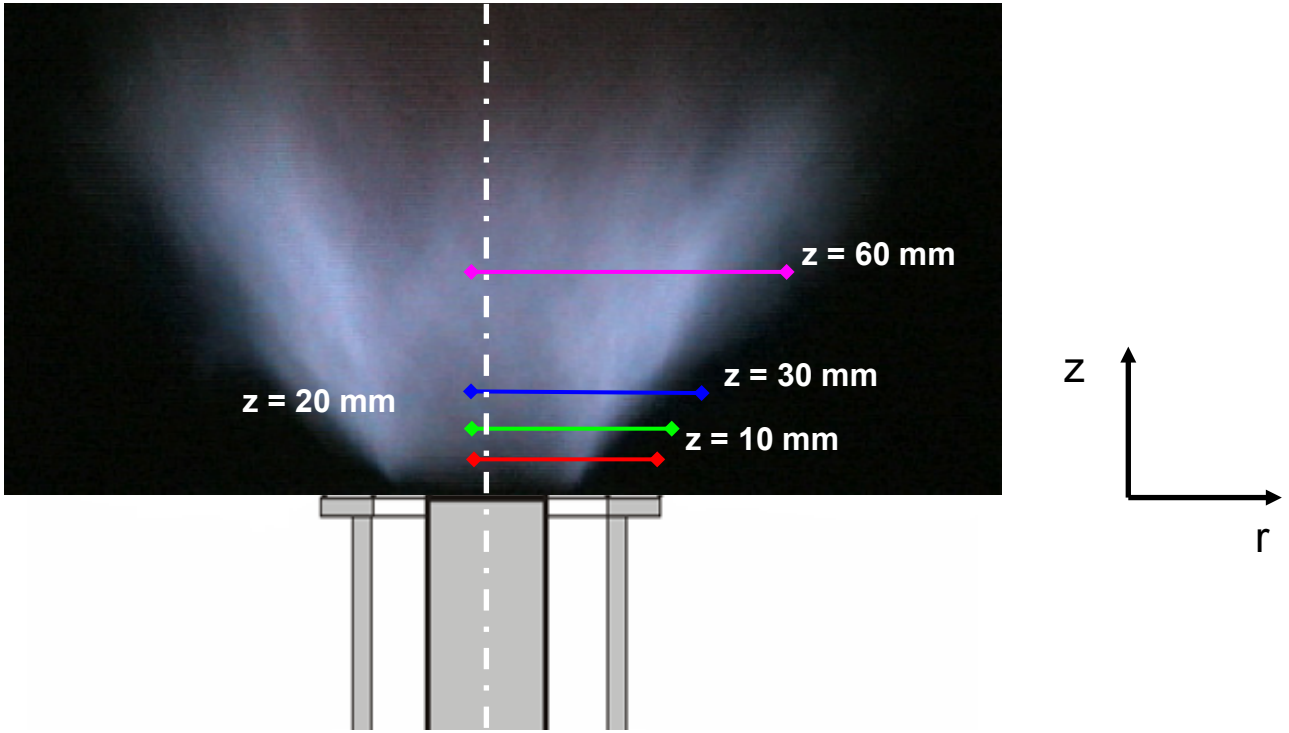
- Radial profiles at 4 axial heights



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Raman scattering – exp. setup

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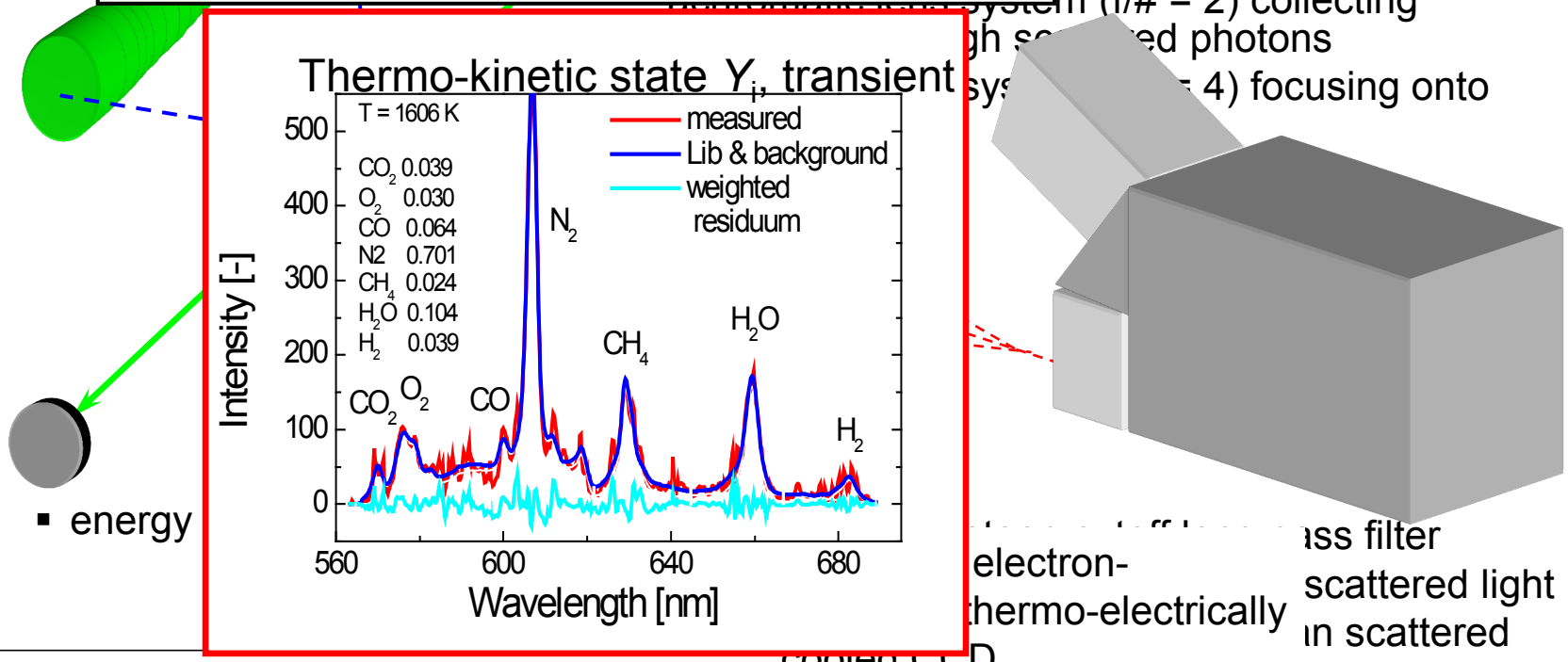
… from delay line

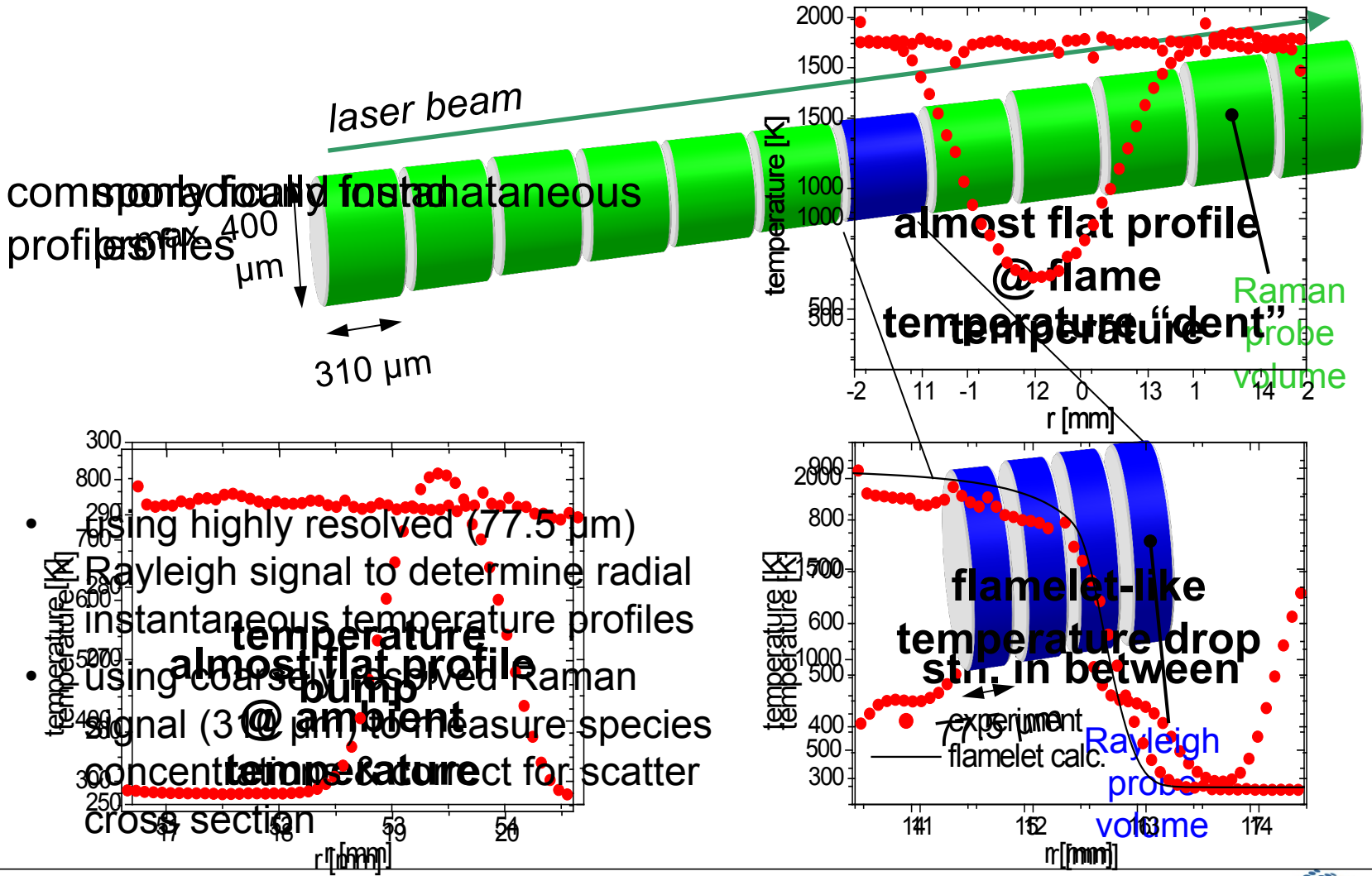
Data evaluation is conducted with a spectral fitting method using theoretical Raman spectra

- 1D probe beam wa… µm
- energy
- ***Raman:*** gating by a rotating …tter (~ 10 µs)
- …pressing spurious light
- …rny-Turner type imaging …ctrometer
- …0
- …mo-electrically cooled …kside illuminated CCD …stem (f/# = 2) collecting …gh s…ed photons …sy… = 4) focusing onto



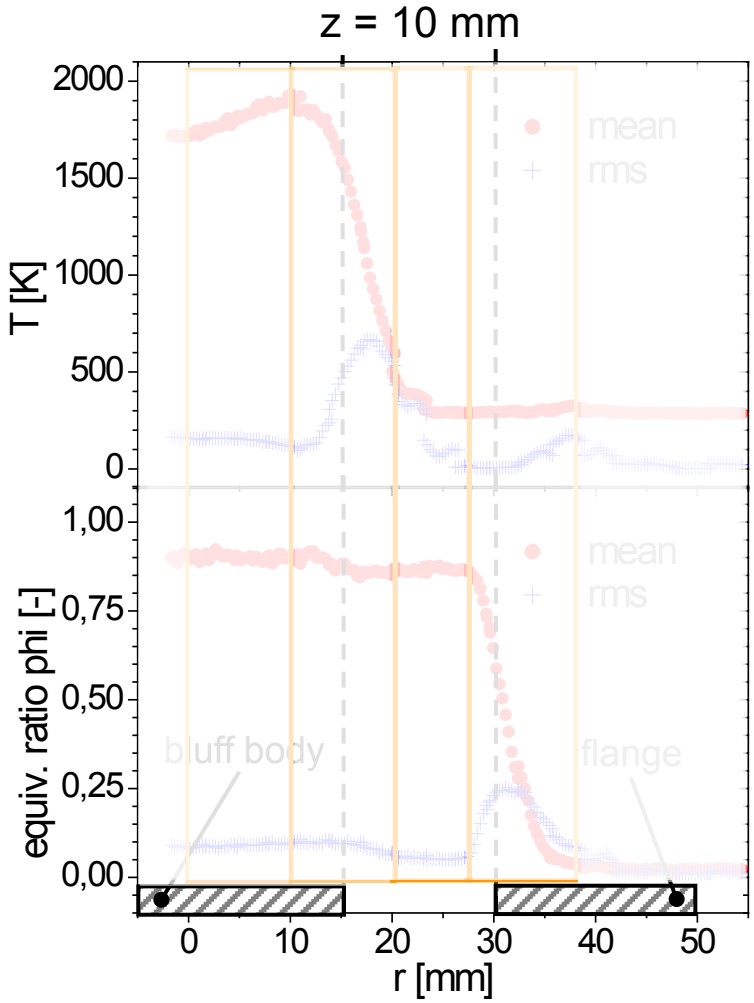
…ass filter
…electron-
…scattered light
…thermo-electrically …n scattered
cooled CCD

Raman scattering – spatial resolution

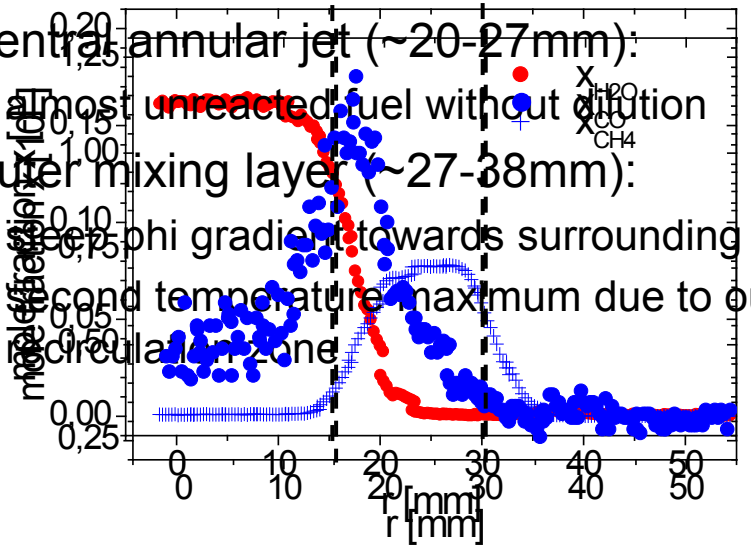


- using highly resolved (77.5 µm) Rayleigh signal to determine radial instantaneous temperature profiles
- using coarsely resolved Raman signal (310 µm) to measure species concentrations & correct for scatter cross section

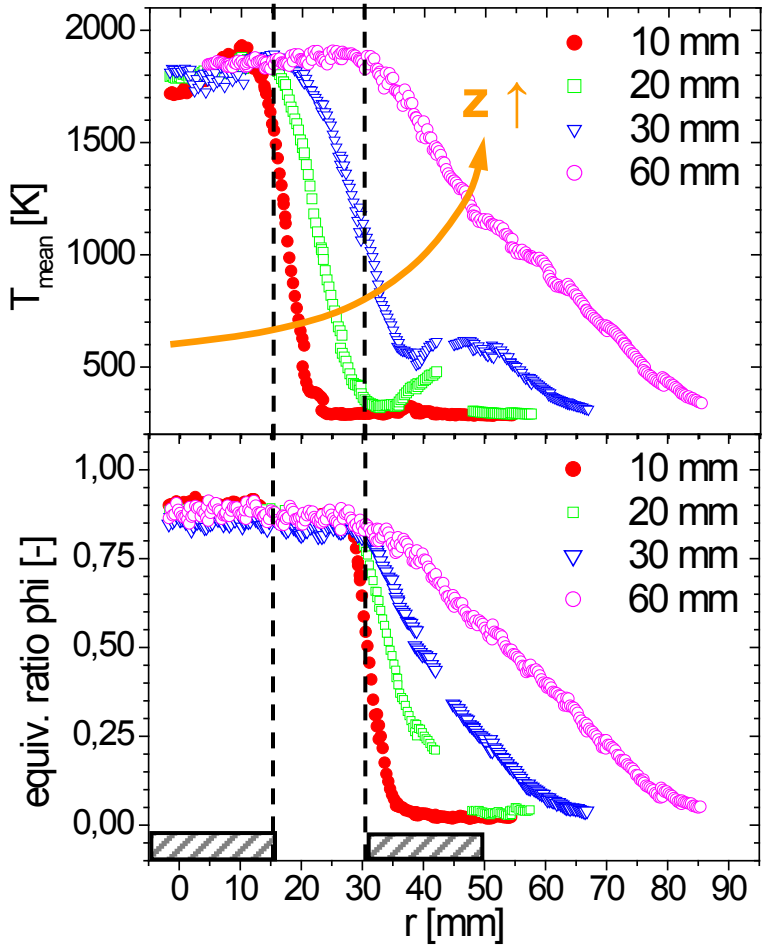
Radial Profiles (mean and rms)



- inner recirculation zone (~0-10mm):
  - fully burnt exhaust
  - heat loss to bluff body
- inner mixing layer (~10-20mm):
  - strong intermittency hence high fluctuation levels
  - r ~ 17 mm: mean premixed flame front position as deduced from max. T & c gradients / max. CO concentration
- central annular jet (~20-27mm):
  - almost unreacted fuel without dilution
- outer mixing layer (~27-38mm):
  - steep phi gradient towards surrounding air (phi = 0)
  - second temperature maximum due to outer recirculation zone



Mean Radial Profiles - z Dependency



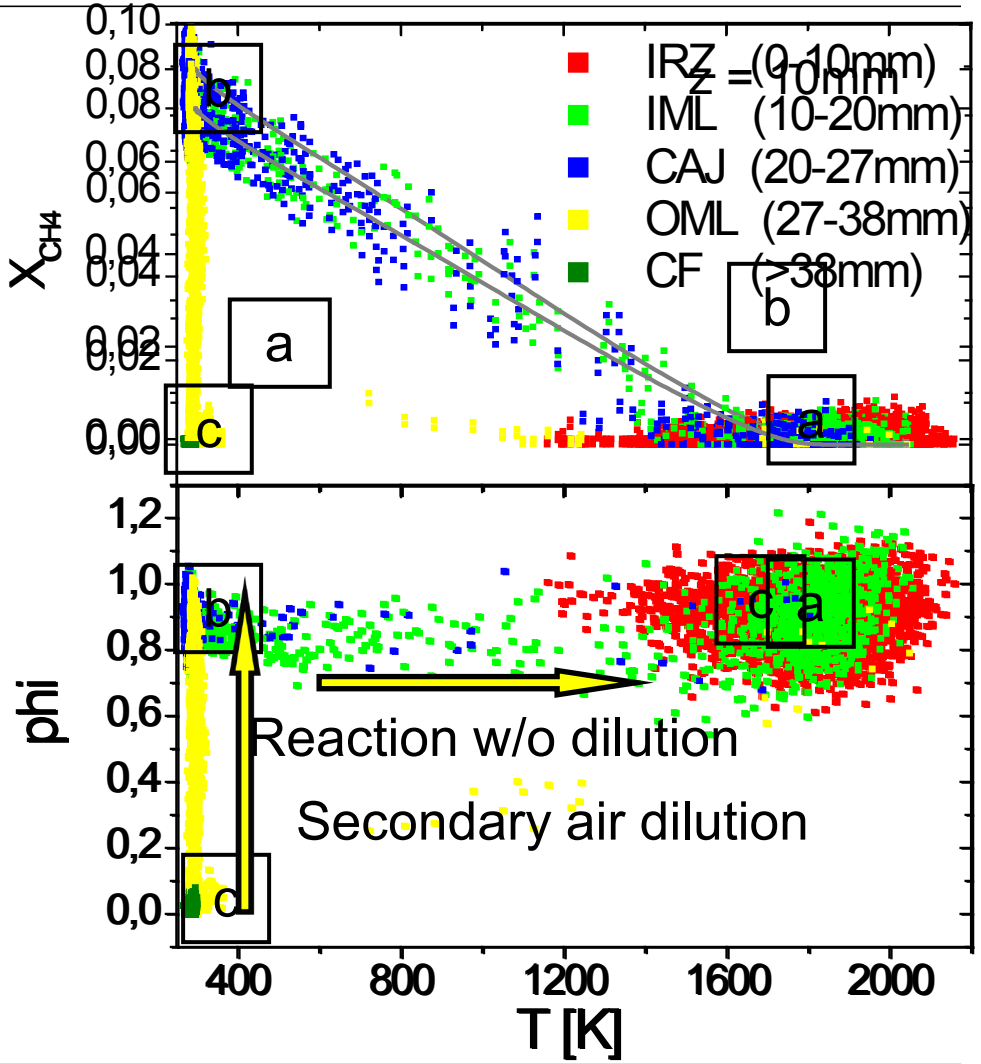
- for increasing height z:
- mean flame front position at larger radii
- wider flame brush & broader mixing layer hence flatter radial T & phi profiles
- distinct 2nd T maximum (up to z = 30mm) due to outer recirculation of exhaust
- premixed flame front is located in regions with very low stratification of nearly constant phi (up to z = 30mm)

Single Shot Correlations - Scatter Plots

- single shot correlation between 2 or more scalars (e.g. T & CH4)
- each scatter corresponds to one single shot
- samples spanned between 3 thermo-kinetic states:
  - a) hot burnt exhaust
  - b) cold unburnt fuel
  - c) cold secondary air

- **samples can be assigned to flame regions:**
  - inner recirculation zone (0-10mm):
    fully burnt samples @ max T, no secondary air
  - inner mixing layer & central annular jet (10-27mm):
    burnt, unburnt or mixed samples, no secondary air
  - outer mixing layer (27 - 38 mm):
    mostly unburnt fuel and / or secondary air

    rarely mixing between burnt samples and secondary air
  - coflow / flange (>38 mm):
    exclusively ambient air



Scatter Plots - z Dependency

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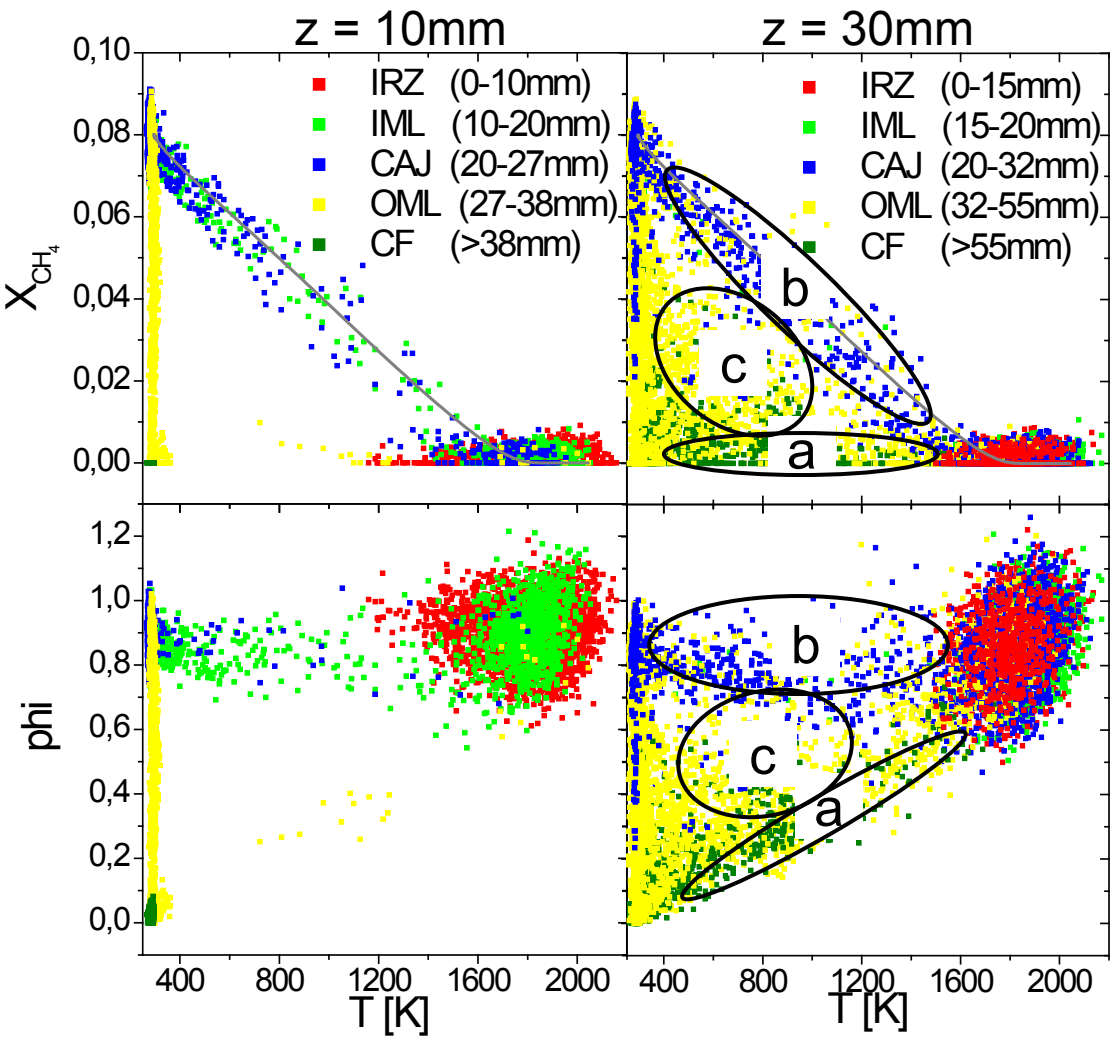
- *at z = 30 mm:*
- significantly increased probability to measure intermediate samples due to:
  - a) secondary air entrainment into burnt exhaust (OML, CF)
  - b) mixing between burnt / unburnt fuel (CAJ) and reaction without dilution
  - c) mixing of air with reacted AND unreacted fuel

    or
  - slowed or extinguished reactions (CAJ, OML, CF)



Conclusions Raman/Rayleigh scattering in swirling premixed flame

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- Temperature is key-quantity (reaction progress)
- Thermo-kinetic state precisely measured
- Thermo-kinetic state is a prerequisite for understanding pollutant formation and finite rate chemistry effects
- Main findings are
  - In region of flame stabilization (z < 30 mm) premixed flame front is not located in areas of stratification but in areas of almost constant phi
  - typical reaction and / or mixing behavior can be assigned to different flame regions
  - intermediate reaction states are promoted by dilution with air
  - distinction between pure mixing and local flame quenching needs additional diagnostics monitoring intermediate species

Chapter 8: High-speed Laser Combustion Diagnostics – General Aspects

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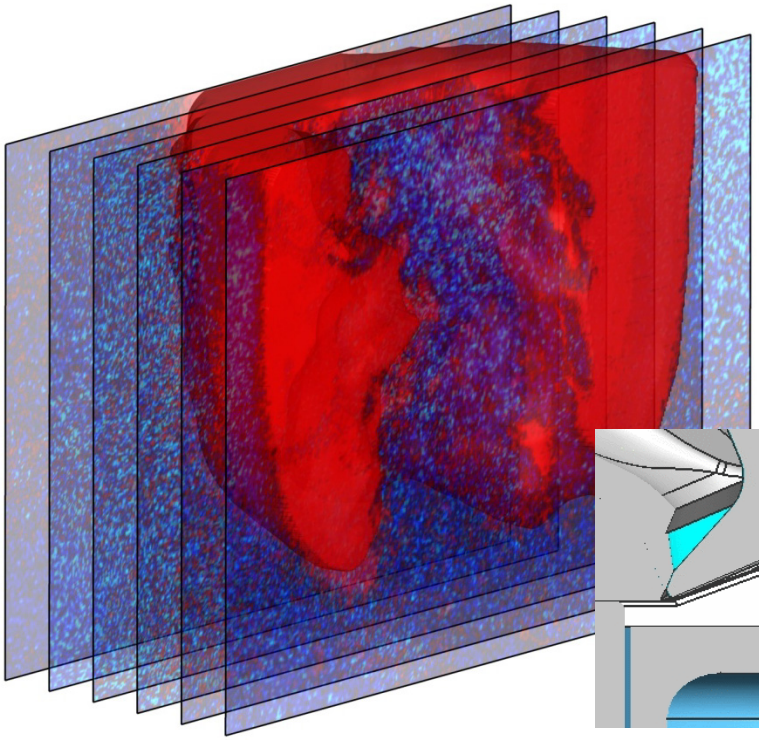
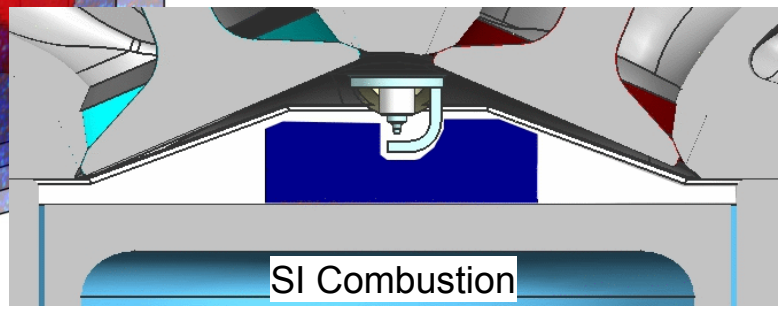
TU Darmstadt, Germany
Mechanical Engineering – Reactive Flows and Diagnostics

A. Dreizler

Photron.com





Contents

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- Why high-speed laser diagnostics?
- Instrumentation
  - High-speed lasers
  - High-speed cameras

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State-of-the-art laser combustion diagnostics

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- Flow and multi-scalar measurements
  - Low sampling rates (<100 Hz)
  - High precision and accuracy
  - Good for measuring statistical moments (single-point, two-point statistics)
  - Example: scatter plots by multi-scalar Raman/Rayleigh spectroscopy

State-of-the-art laser combustion diagnostics

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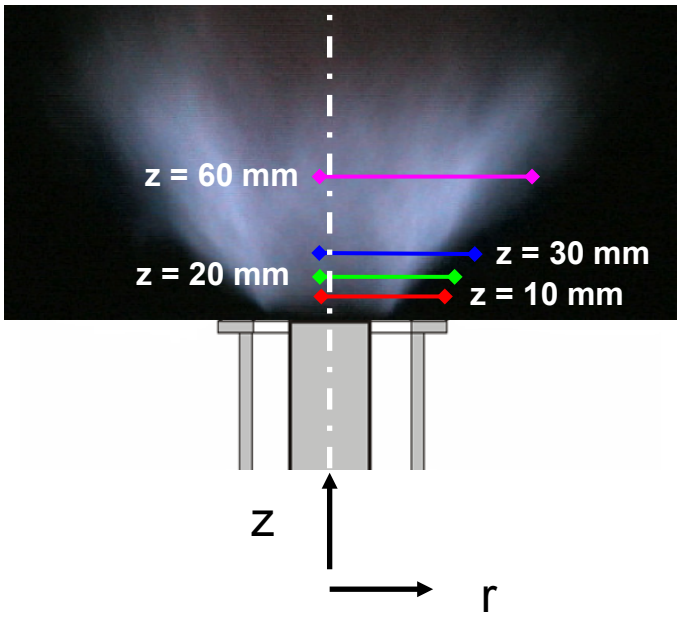
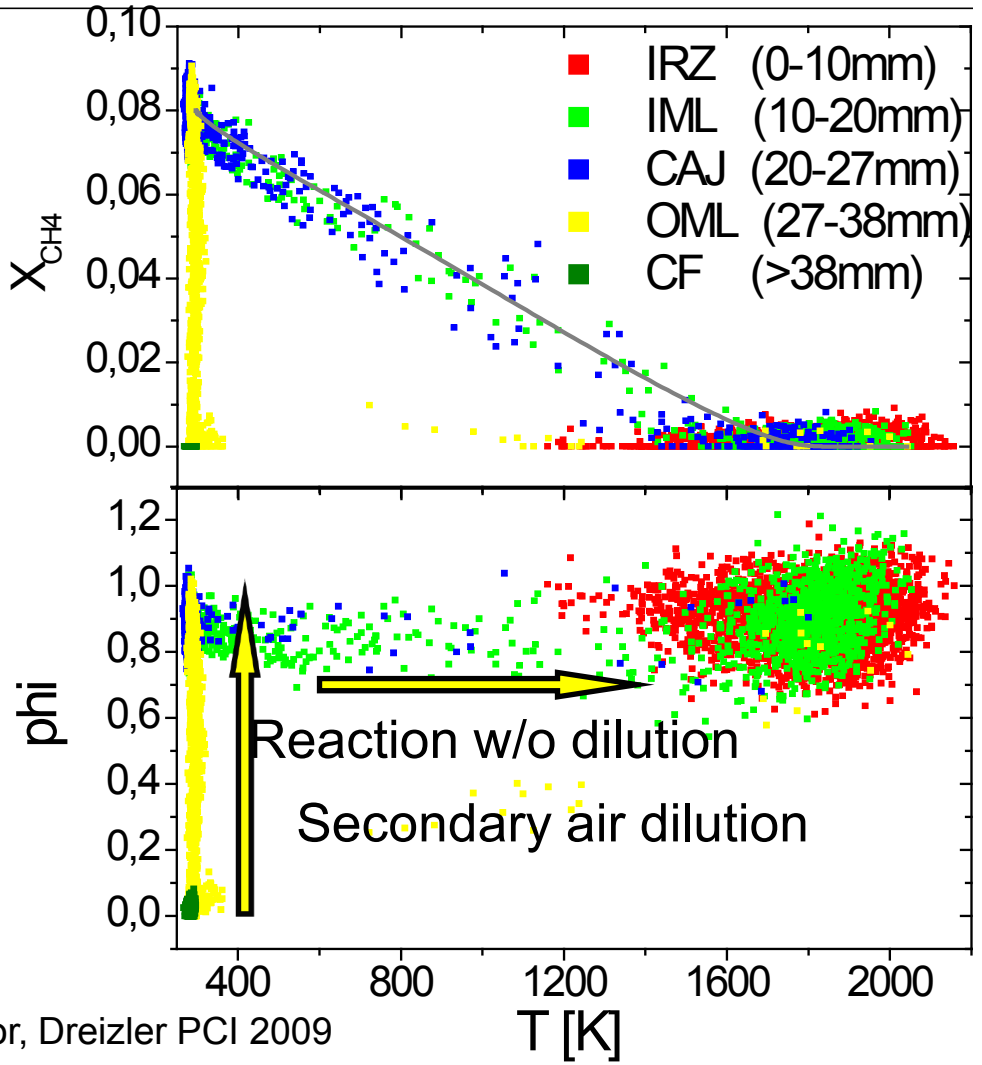
- Example: scatter plots by multi-scalar Raman/Rayleigh spectroscopy, lean premixed swirl flame





Gregor, Dreizler PCI 2009

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Motivation for high speed diagnostics

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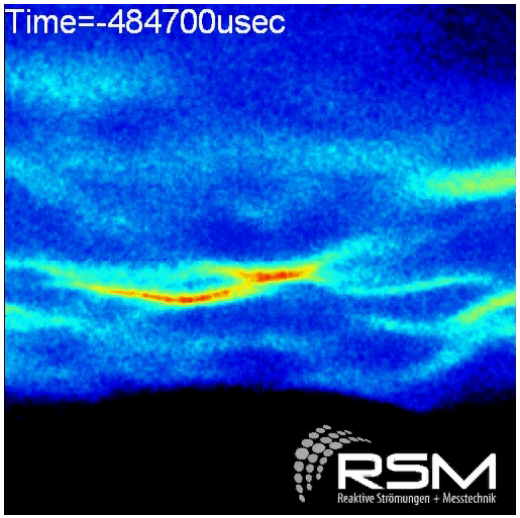
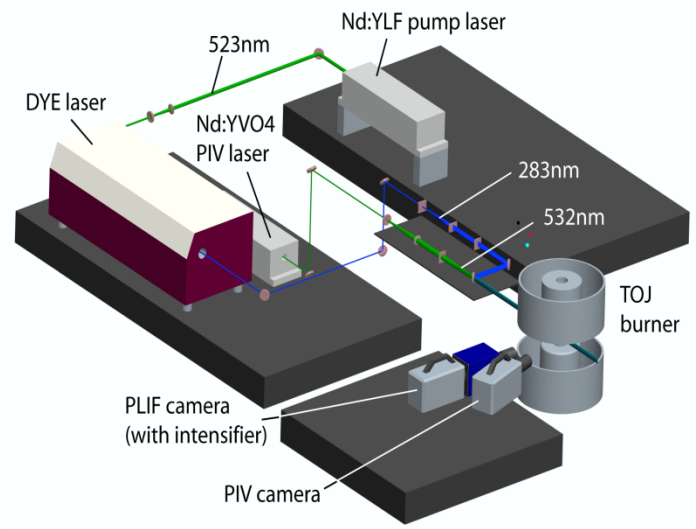
- Example flame extinction (w/o subsequent re-ignition)
  - Here turbulent opposed jet flows, partially premixed flame
  - Bulk flow rates close to global extinction



Böhm, Dreizler PCI 2009



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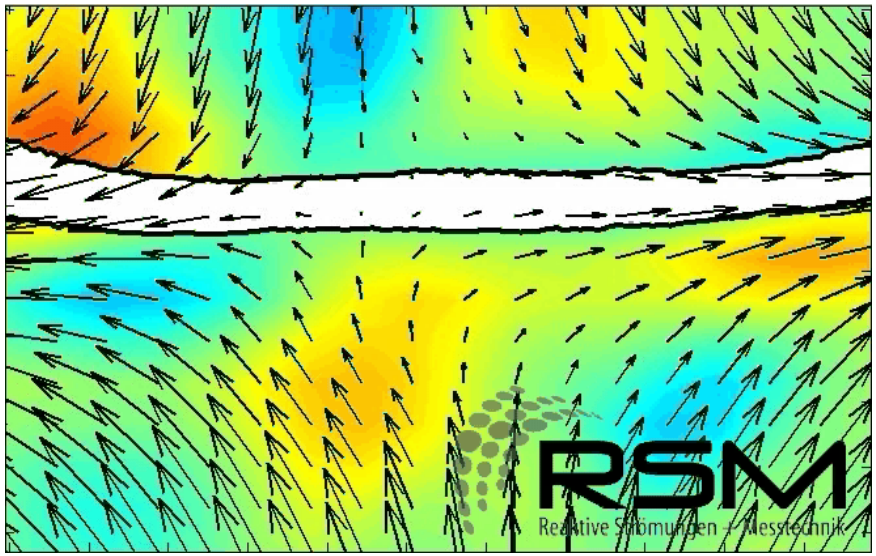
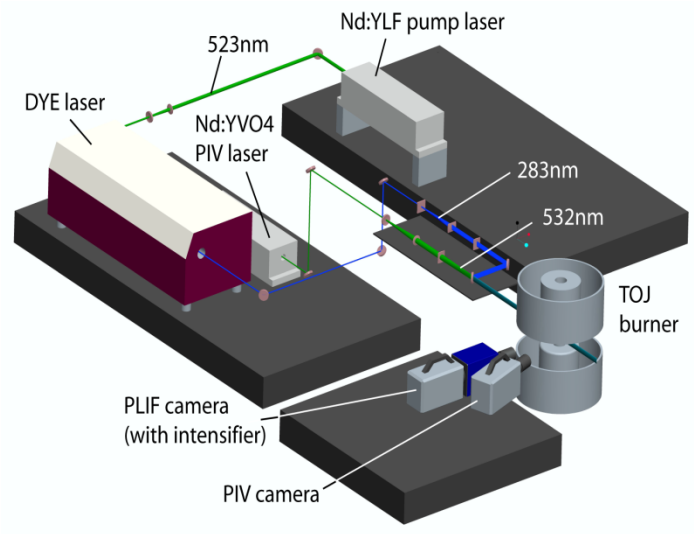
  - Here turbulent opposed jet flows, partially premixed flame
  - Bulk flow rates close to global extinction





Böhm, Dreizler PCI 2009

→ **Tracking extinction needs high sampling rates, post event-triggering and sequence lengths over 10 – 100ms**

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Individual extinction events

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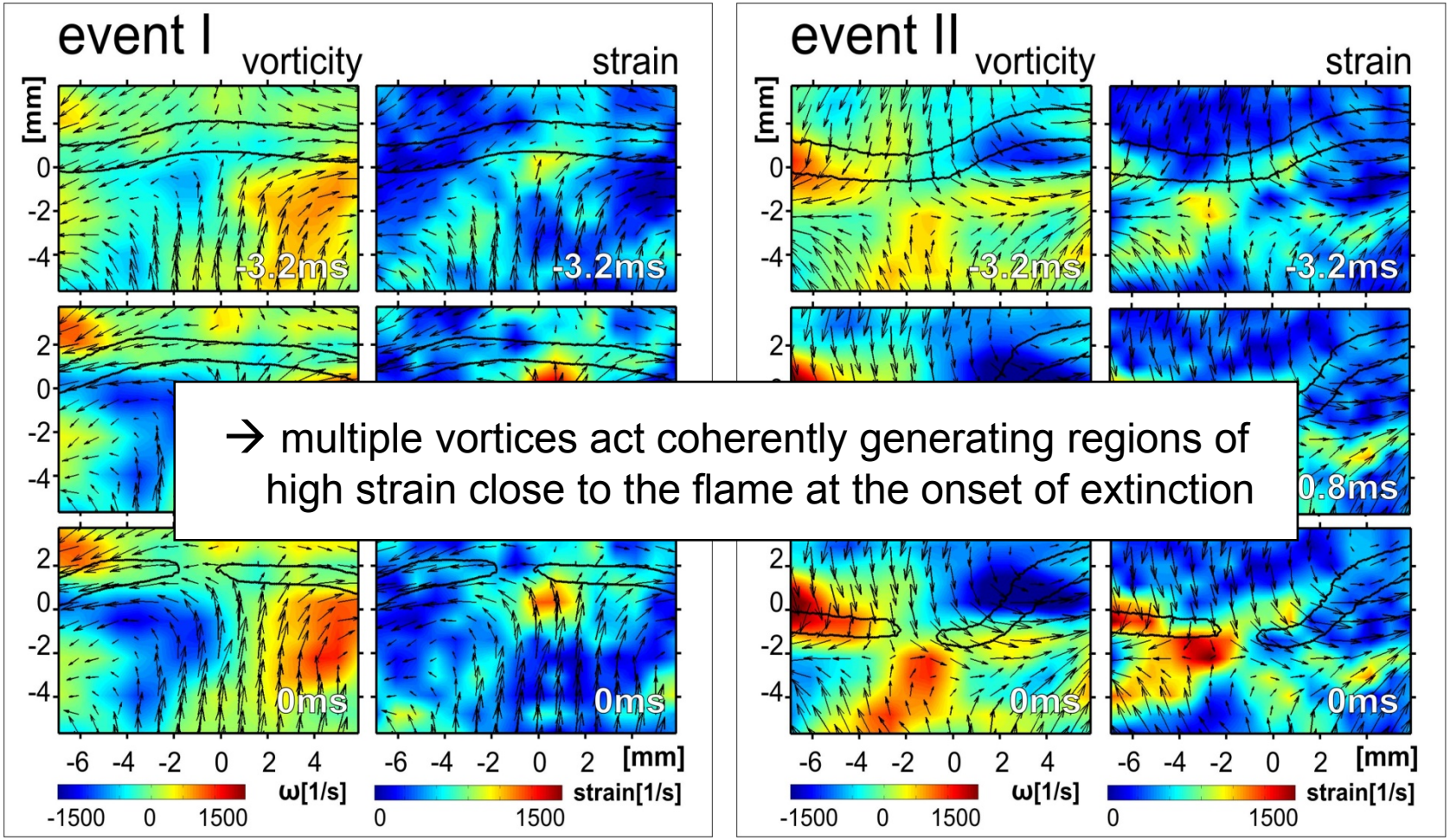

→ multiple vortices act coherently generating regions of high strain close to the flame at the onset of extinction

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Conditional averages

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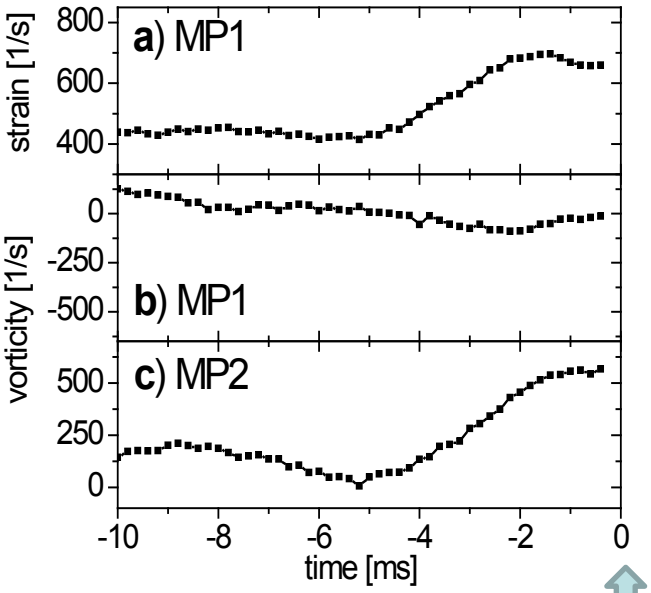
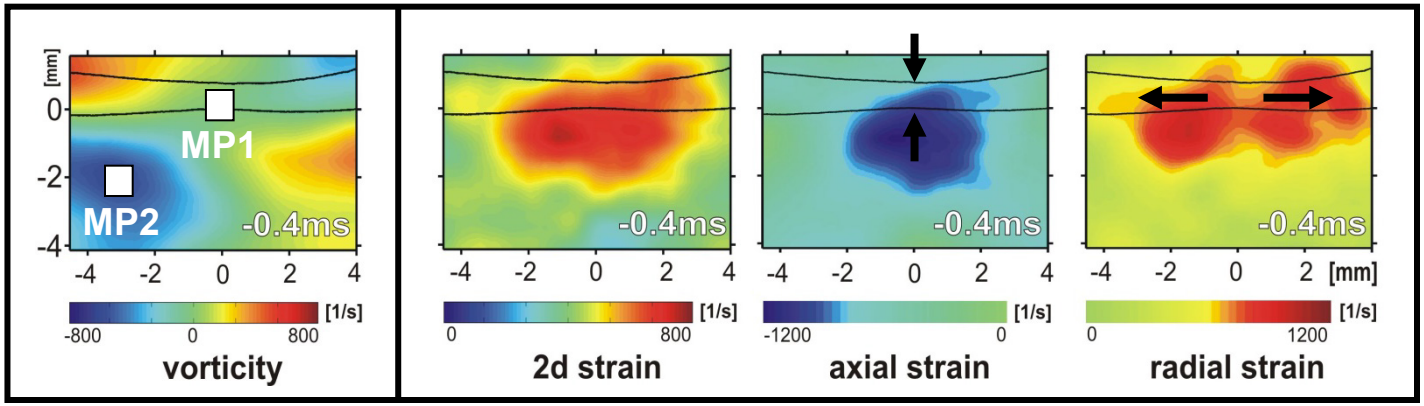
- → Maximum of axial strain surrounded by maxima of radial strain
- → Imposed strain requires time to cause extinction
- → Time history is important
- → Diffusion requires time to reduce scalar gradients



extinction



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Multi-parameter diagnostics at high speed

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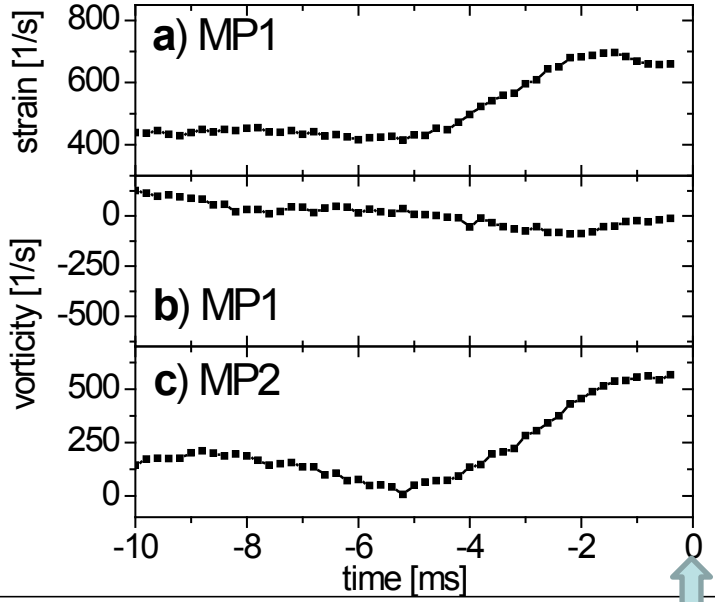
- Simultaneous measurement of velocity fields and qualitative scalar fields that mark features of flames (such as flame fronts) allows determination of conditional velocities:
  - Switch from lab-coordinates to flame-fixed coordinates
  - De-convolute effects from intermittency
  - Better observation of interaction between flow and scalar fields
  - Conditional strain
  - Conditional vorticity



extinction

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Transient phenomena in combustion research

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- Phenomena requiring high speed diagnostics for better understanding
  - Extinction and re-ignition
  - Flame stabilization of lifted flames and flame propagation
  - Flashback in nozzles
  - Auto- and spark-ignition
  - Cycle-to-cycle variations in IC engines
  - 4D-imaging

- What repetition rate is needed?

Typical time scales – lab-scale turbulent premixed flame

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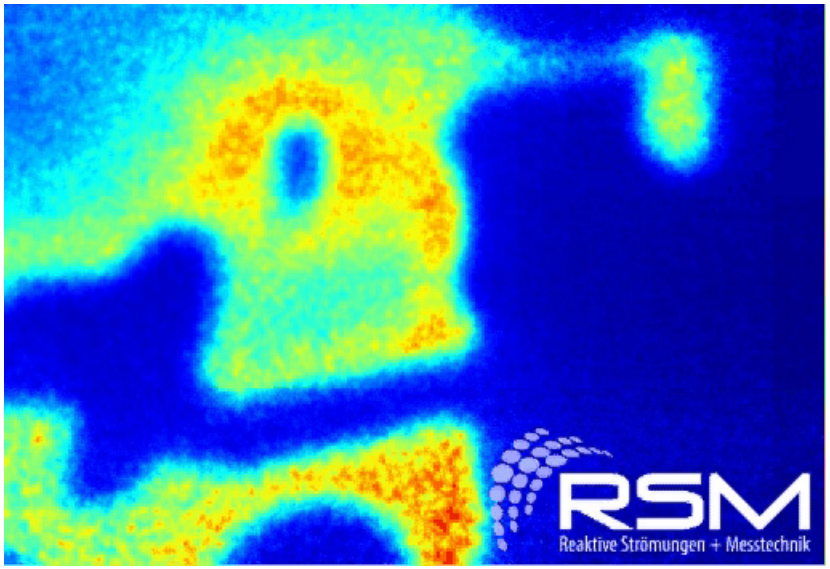
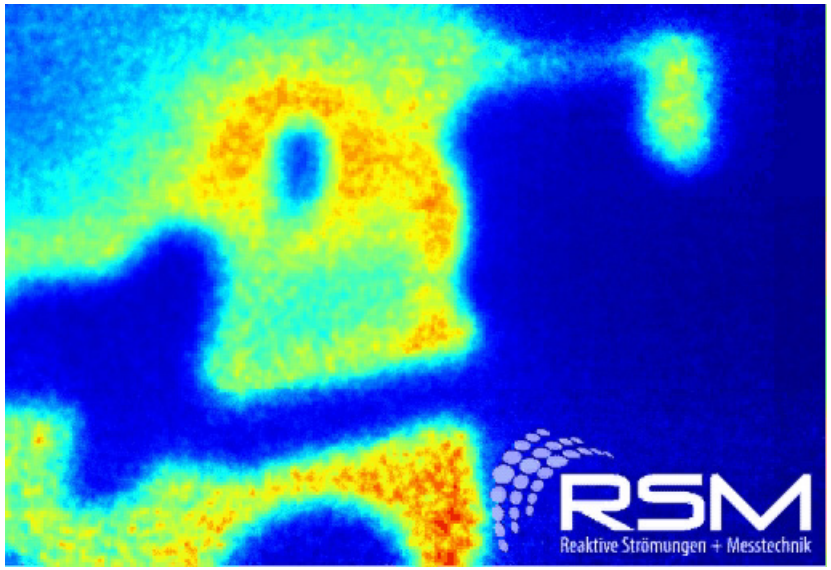
- T_{int} ~ 1.0ms → Sampling rate (0.1 x T_{int}) ~ 100µs → 10 kHz

OH PLIF @ 5 kHz



sequence “judders”

@ 10 kHz



sequence runs “smoothly”

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Typical time scales – IC engine

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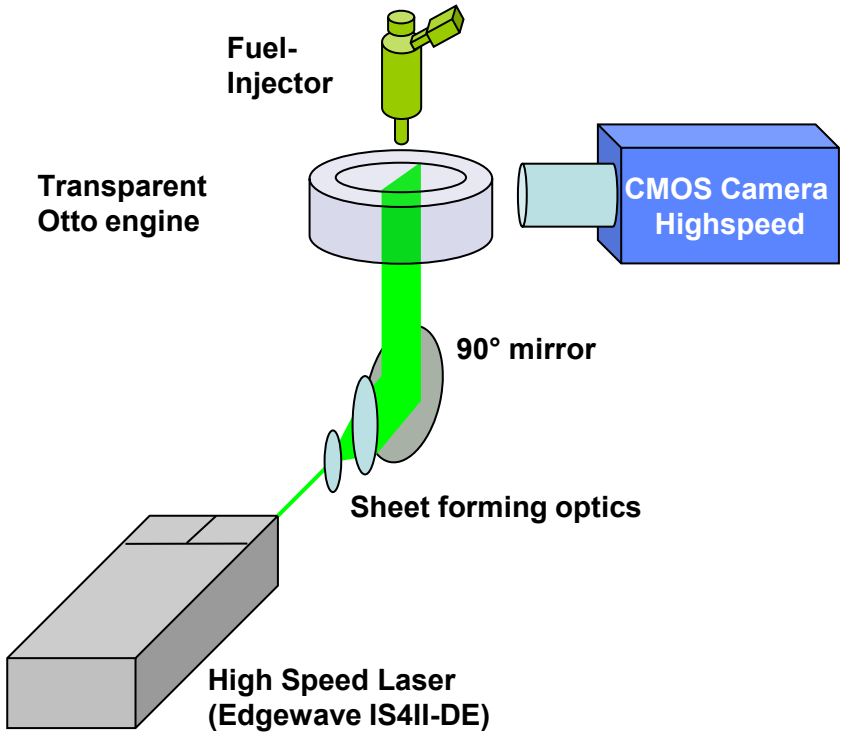
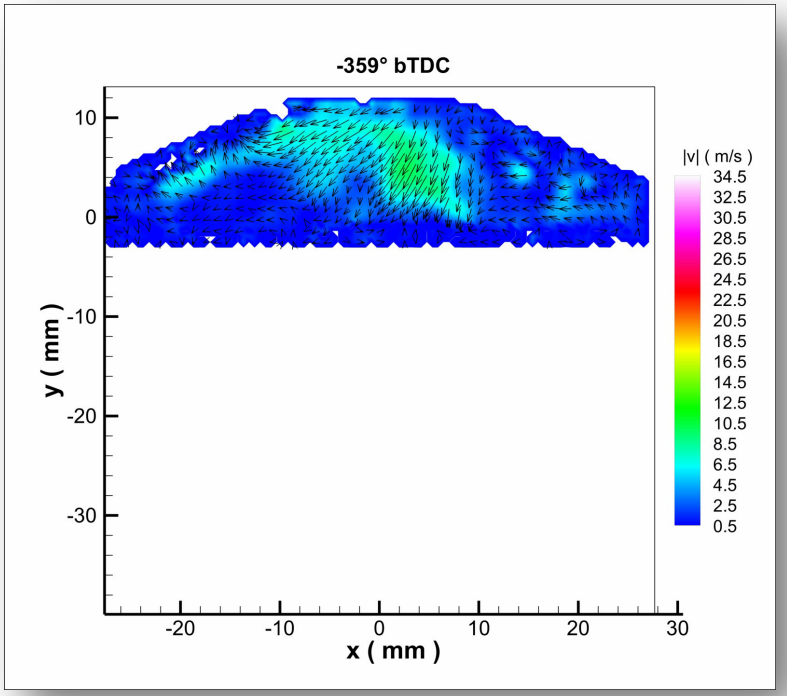
- IC engine operating at 1000 rpm → resolving 1 °CA corresponds to 166 µs → 6 kHz





Flow field during compression
@ 6 kHz 2C-PIV;

E. Baum, et al. *Flow Turbulence Combust.* 92, 269-297 (2014)

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Statistically correlated measurements: Scales to be resolved – integral time scale (T_{int})

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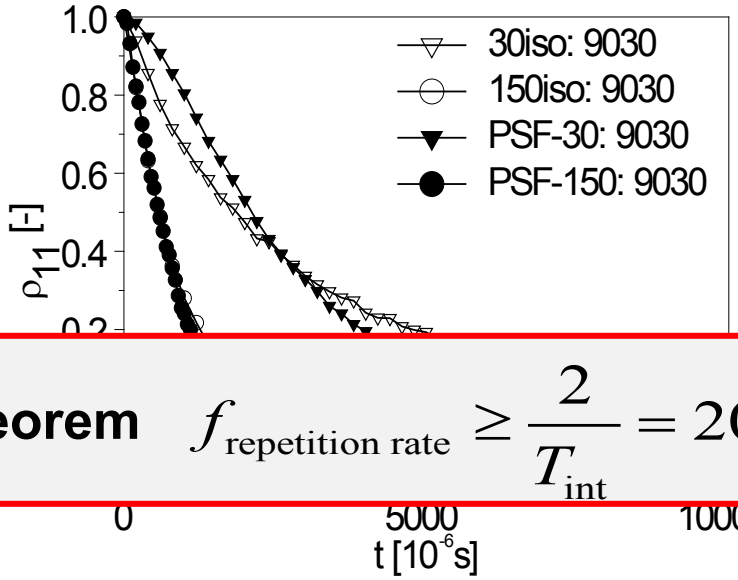
- Swirling annular flow: non-reacting and premixed flame (lab scale)

Iso-pressure surface
Janicka et al. 2007

Re = 10,000 – 40,000

P_{th} = 30 – 150 kW



T_{int}~1.0 ms
=10,000)

Nyquist-Shannon theorem $f_{\text{repetition rate}} \geq \frac{2}{T_{\text{int}}} = 2000 \text{ fps}$

Schneider et al.
FTaC 2005

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Scales to be resolved – Kolmogorov time scale

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- Kolmogorov time scale τ_K (integral length scale L_{int} from 2-point correlations)

$$\tau_K = \left(\frac{\nu}{\varepsilon}\right)^{0.5} \quad ; \quad \varepsilon = \frac{k^{1.5}}{L_{\text{int}}}$$

Example

Swirl flame

Re = 40,000/10,000

τ_K~ 100 µs (representative estimate)

- Nyquist-Shannon theorem

$$f_{\text{frame rate}} \geq \frac{2}{\tau_K} \quad \Longrightarrow \quad f_{\text{frame rate}} \geq 20000 \text{ fps}$$

Imaging:
Fulfilled by state-of-the art CMOS camera technology

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Interdependency of time and length scales

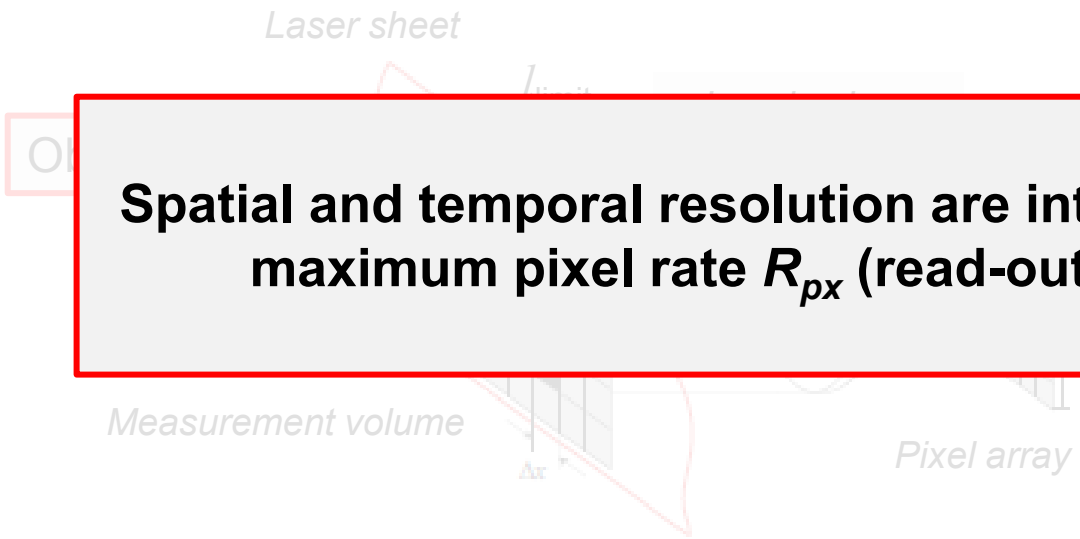
- Field of View: $l_{\mathrm{FOV}} = n_x \cdot \Delta x = n_x \cdot l_{px} \cdot M$
- Nyquist-Shannon: $l_{\mathrm{limit}} \geq 2 \cdot \Delta x$

Pixel rate

Temporal resolution

$$\frac{l_{\mathrm{FOV}}}{l_{\mathrm{limit}}} = \frac{1}{2}\sqrt{\frac{R_{px} \cdot \tau_{\mathrm{limit}}}{2}}$$

Spatial dynamic range



Spatial and temporal resolution are interconnected via the maximum pixel rate R_{px} (read-out-rate of CMOS)

Interdependency of time and length scales

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$$R_{px} = 20 \cdot 10^9 \ \text{px/s}$$

$$\text{Magnification} = 1$$

$$\tau_{limit} = \tau_K = 100 \ \mu\text{s}$$

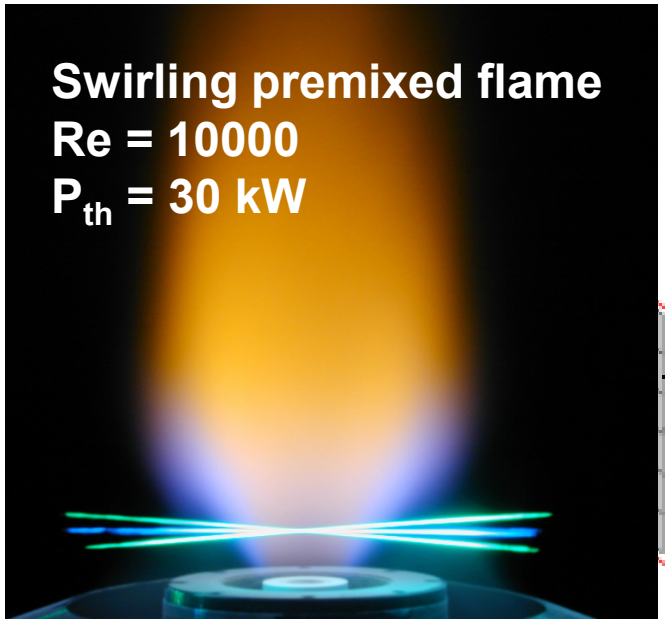
$$l_{FOV} = 20 \ \text{mm}$$

$$\frac{l_{FOV}}{l_{limit}} = 500 \Rightarrow l_{limit} = 40 \ \mu\text{m}$$

Spatial dynamic range

$$l_K = \left(\frac{\nu^3}{\varepsilon} \right)^{0.25} \Rightarrow l_K = 50 \ \mu\text{m}$$

Same range



Imaging lens
Magnification M

l_{px}

Lab flames, present CMOS technology:
Kolmogorov length and time scales resolvable
FOV contains 2-5 integral length scales

Pixel array

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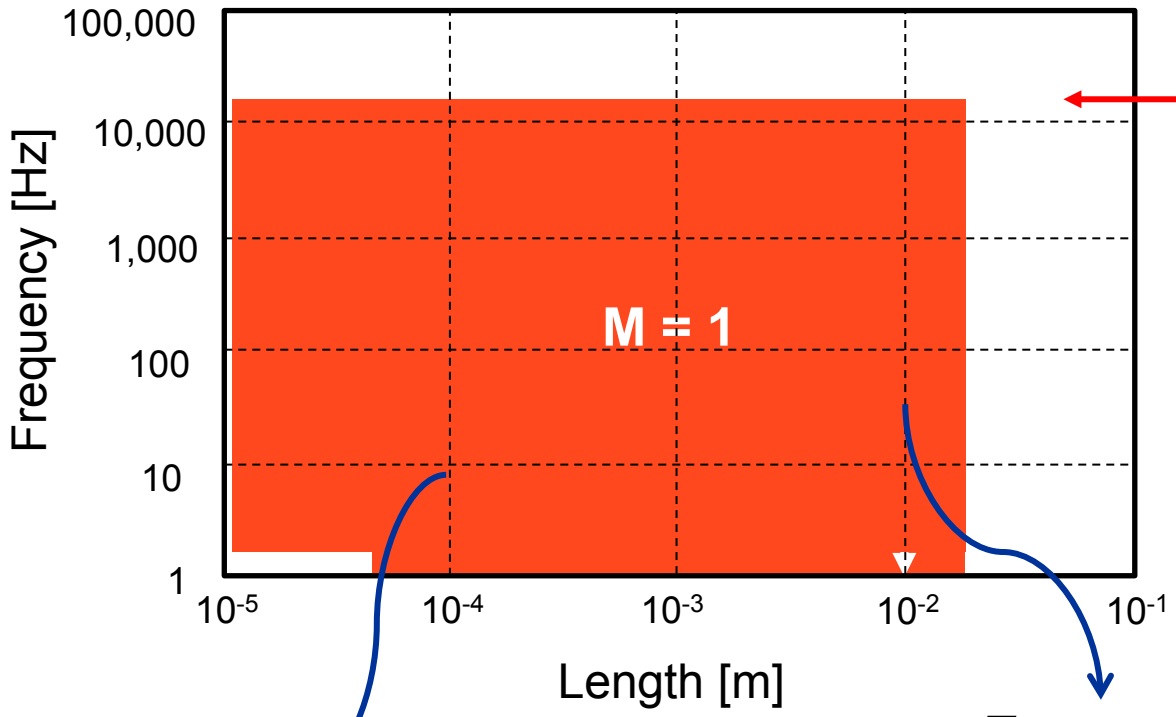
Dynamic ranges – spatial and temporal



Max. frame rate at full frame
(~ 1 Mio. Pixels)

$$\frac{l_{\text{FOV}}}{l_{\text{limit}}} = 500$$

$$\frac{T_{\text{meas. time}}}{\tau_{\text{limit}}} = \frac{T_{\text{meas. time}}}{2} f_{\text{frame rate}} = 10,000$$

Nyquist, on-board memory CMOS

Application high speed diagnostics – examples

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- Field of application
  - Experiments where only few realizations or short measurement periods are available (shock tubes, IC engines, …)
  - Transients in combustion
    - ignition, extinction
    - blow off, flashback
    - flame propagation, cyclic variations …

  } (conditional) statistics
- Instrumentation specific to spectral range and diagnostic method
  - Towards 4D imaging (3D in space + time) → new high speed lasers and CMOS cameras

Ex2: High speed imaging

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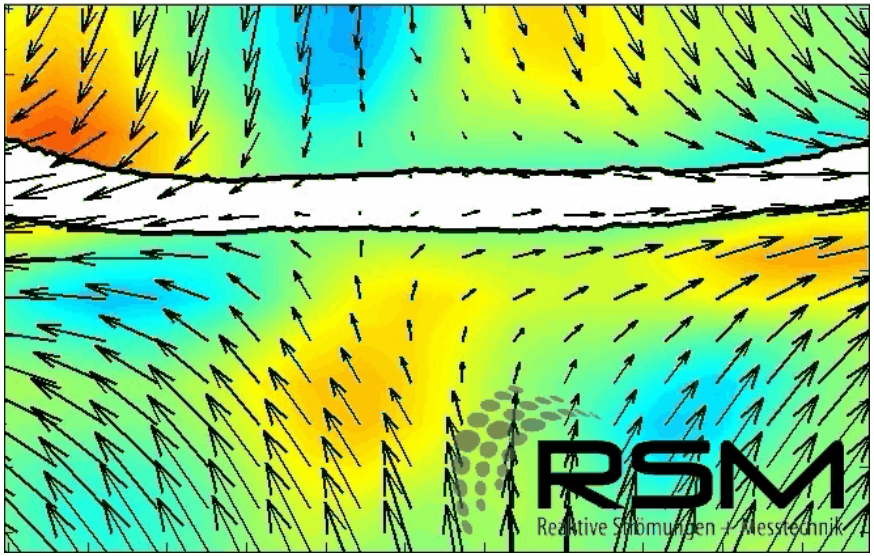
- Rapid progress of laser and camera technology over the last 6-8 years
- Recent reviews on high speed imaging
  - Böhm et al. (FTaC 2011)
  - Thurow et al. (MST 2013)
  - Sick (PCI 2013)
- Requirements
  - High power lasers
  - High frame rate cameras



Extinction in turbulent opposed jet flame
B. Böhm et al. PCI 2009

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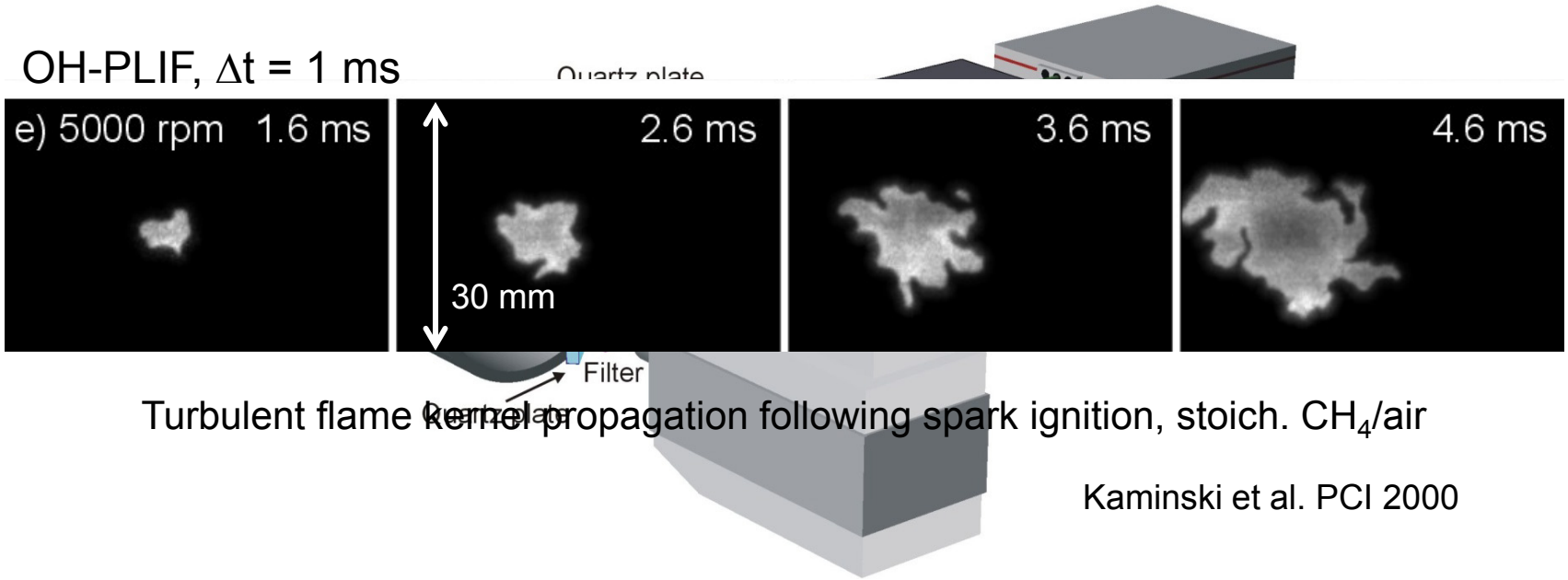
Burst lasers for high speed imaging

- Low duty cycle, high pulse energies
  - Aldén group (Lund)
    - Cluster of 4 Nd:YAG lasers, frequency doubled
    - 4 – 8 pulses/burst, <500mJ/pulse
    - Use of harmonics directly or for pumping a dye laser/dye laser cluster

OH-PLIF, Δt = 1 ms



Turbulent flame kernel propagation following spark ignition, stoich. CH_4/air

Kaminski et al. PCI 2000

Lund multi-YAG

Burst lasers for high speed imaging

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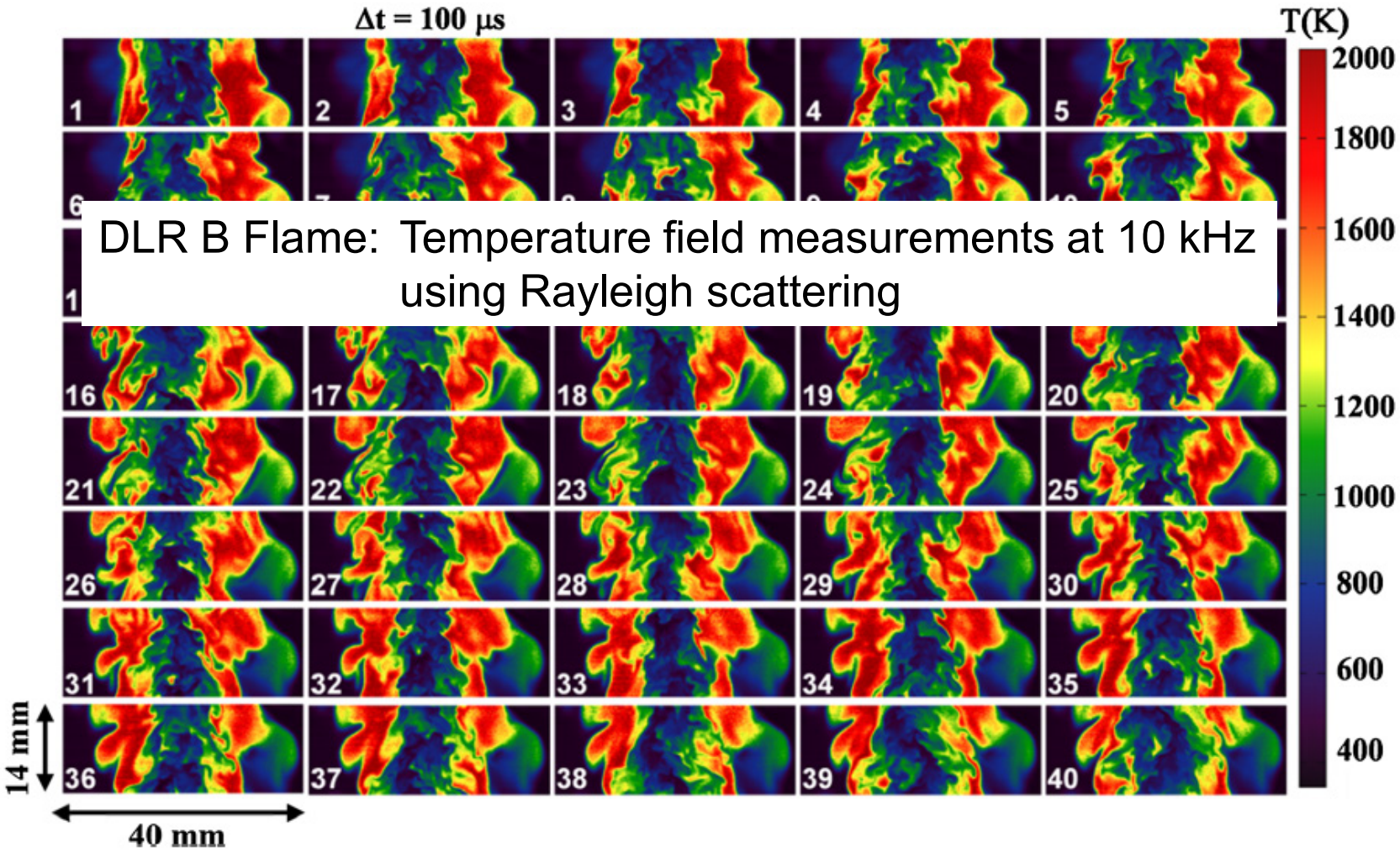

DLR B Flame: Temperature field measurements at 10 kHz using Rayleigh scattering

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Continuously pulsed high speed lasers

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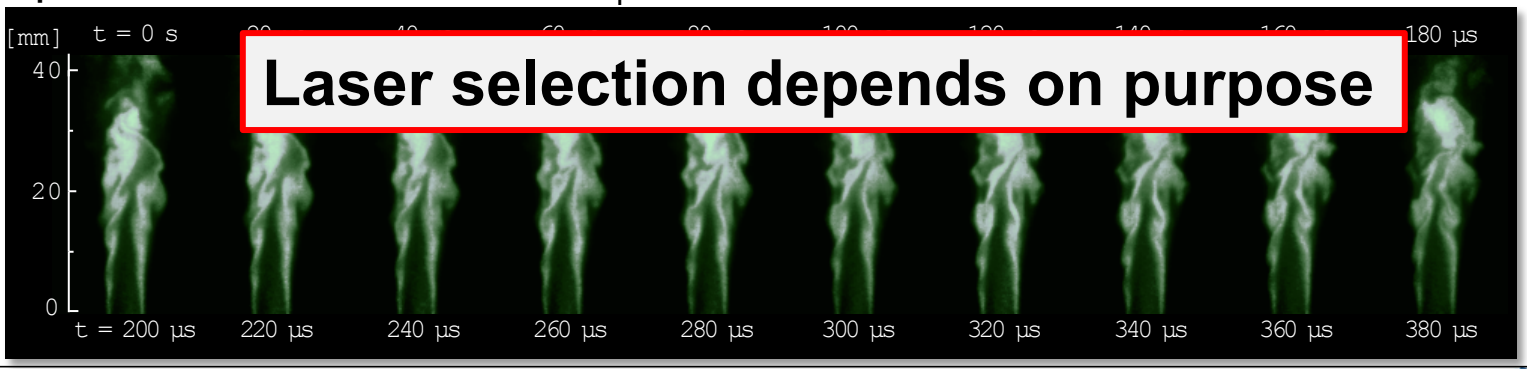
- High duty cycle, low pulse energies
  - Long pulse-lasers: Δt_{laser} > 100ns → intra-cavity conversion for VIS, UV generation
  - Short pulse-lasers: Δt_{laser} < 20ns → extra-cavity conversion for VIS, UV generation
    - Suitable to pump dye lasers
    - Most recent specifications:
      - 50 kHz, 200 W pump power @ 532 nm → 7 W @ 283nm (2-step SHG)

        S. Hammack, C. Carter, C. Wünsche, T. Lee: Appl. Optics (2014)

        plasma-torch stabilized CH_4/air flame



Laser selection depends on purpose

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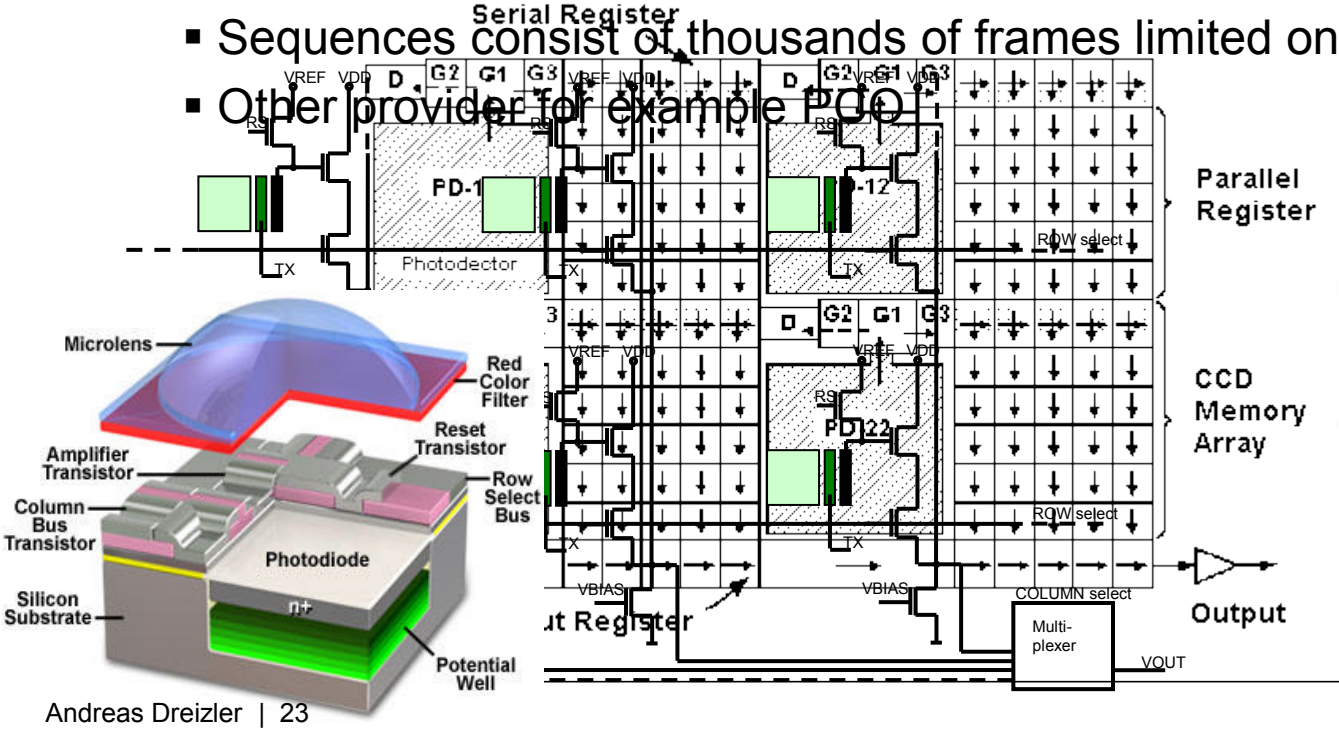
Instrumentation – cameras

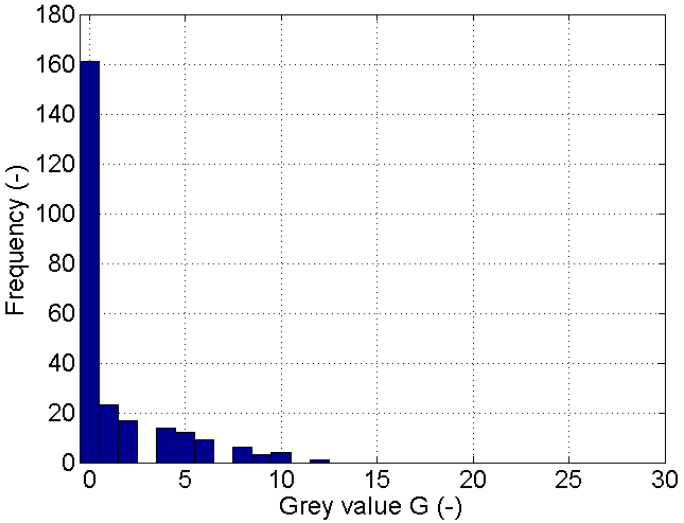
- High speed cameras
  - Multi-frame CCD´s cameras
  - CEOS cameras
    - Example Princeton Scientific Instruments PSI 4
      - Example Phantom v25.12 (28 frames, 3 MHz, 80x160 pixels, 14 bit)
        (1280 x 800@ 25,000 fps, 128 x 16 pixels @ 1,000,000 fps)
      - Sequences consist of thousands of frames limited only by onboard memory
      - Other provider for example PCO

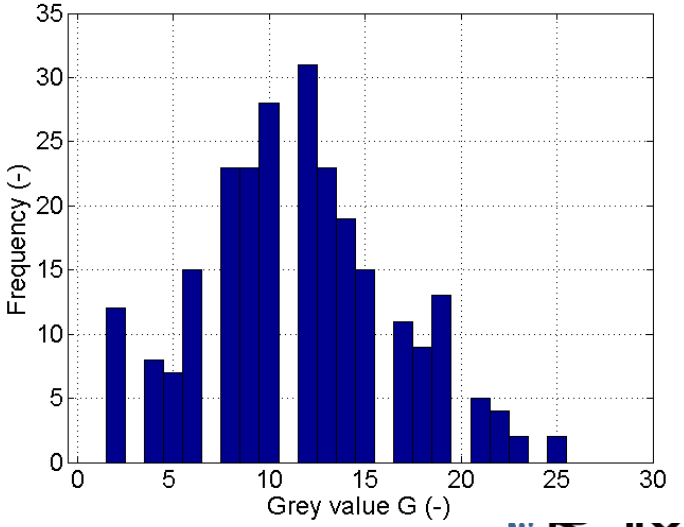


Photron

CMOS – basic sensor checks

- High speed CMOS not yet temp. stabilized
  - → Significant temperature drift, independent on illumination
  - → Wait for thermal equilibrium
- Truncated dark noise with “intensity calibration”
  - → Switch off intensity calibration
- Vacancies in grey value resolution due to pixel gain
  - → Reduces dynamic range
  - → Introduces larger digitization noise





Weber, Dreizler APB 2011

CMOS – Non-linearity

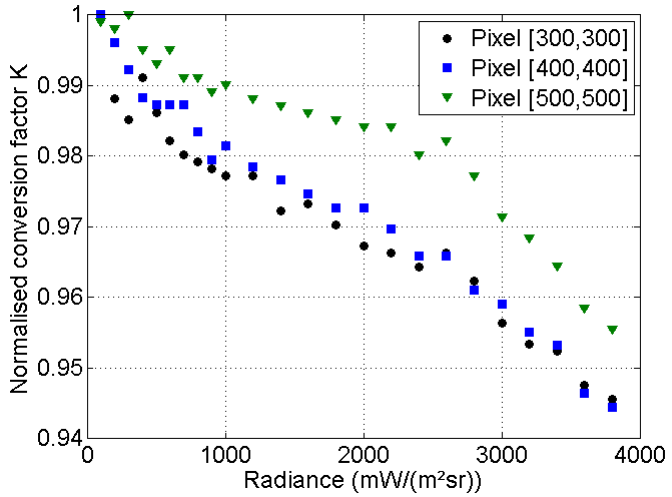
- Checking camera response (pixelwise)
  → Homogenous calibrated light source (Ulbricht sphere)

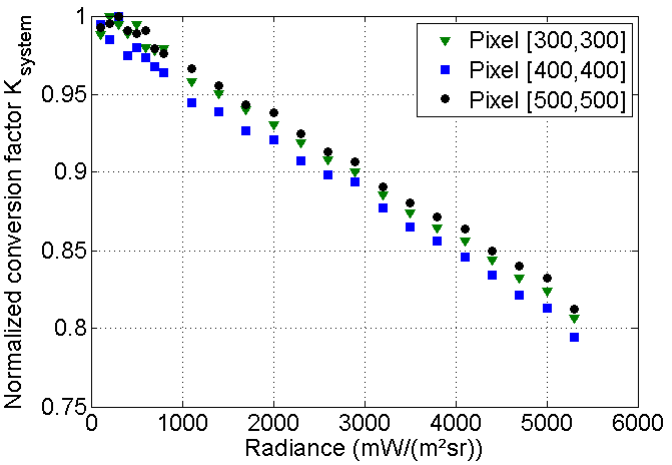
- Model for pixel response as

$$G_i = G_{0,i} + K_{i,N_{e,i}} N_{e,i}$$

  → Inherent non-linear response
  → Deviations from linearity < 6%

- Inclusion of image 2-stage-intensifier (MCP + booster)
  → Significantly increased non-linearity





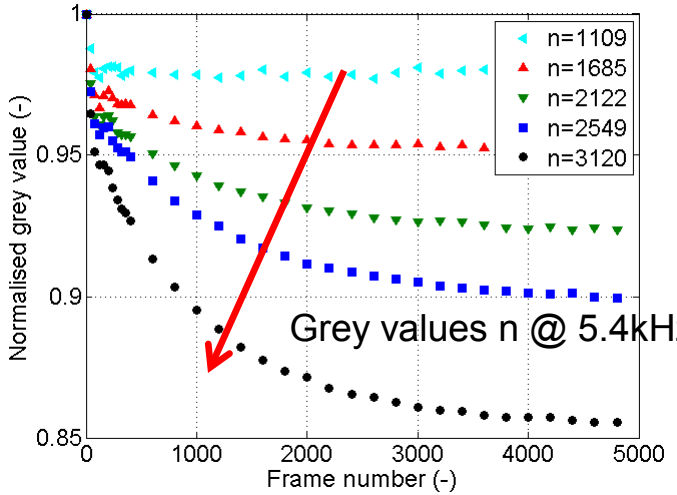
CMOS – image intensifier signal depletion

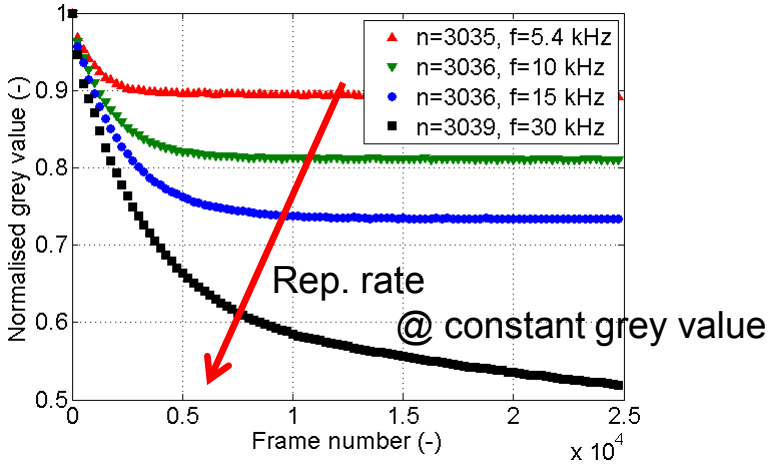
- Intensified systems suffer from signal depletion
- Full sensor illumination: Depletion increases with signal intensity (grey value n) and repetition rate

→ Without correction: device is unable to reproduce a constant signal within the first few 2000 frames

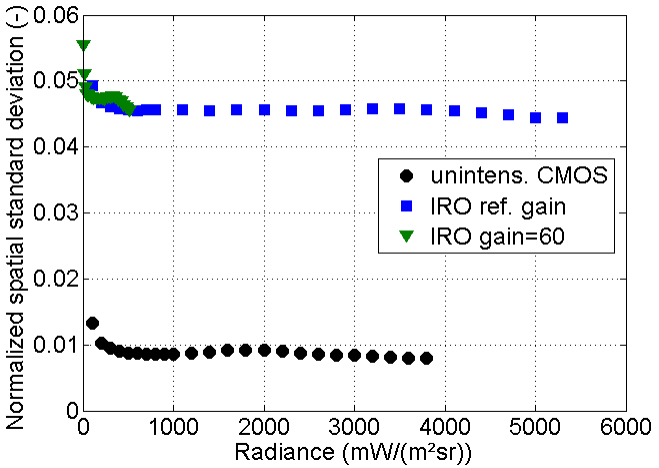
- Dependent on
  - Signal intensity
  - Frame rate
  - Exposure time
  - Illuminated area

  → <u>In-situ calibration required</u>





CMOS – quantitative measurements



- Unintensified CMOS camera (preferred)
  - Resolve dark signal (disable IC)
  - (Pixelwise) correction of nonlinearity
- Intensified CMOS
  - Pixelwise correction of nonlinearity
  - Signal depletion. No best practice advice available

  → Solution: monitor depletion with spot of known illumination?
  - "Halos" (steep intensity gradients cause cross-talk to neighboring pixels)?

→ Each CMOS camera/ intensifier has unique characteristics

→ Need for common calibration procedure

→ EMVA 3.0 not suitable for our needs

Chapter 8:
Towards 4D-imaging

TU Darmstadt, Germany
Mechanical Engineering – Reactive Flows and Diagnostics

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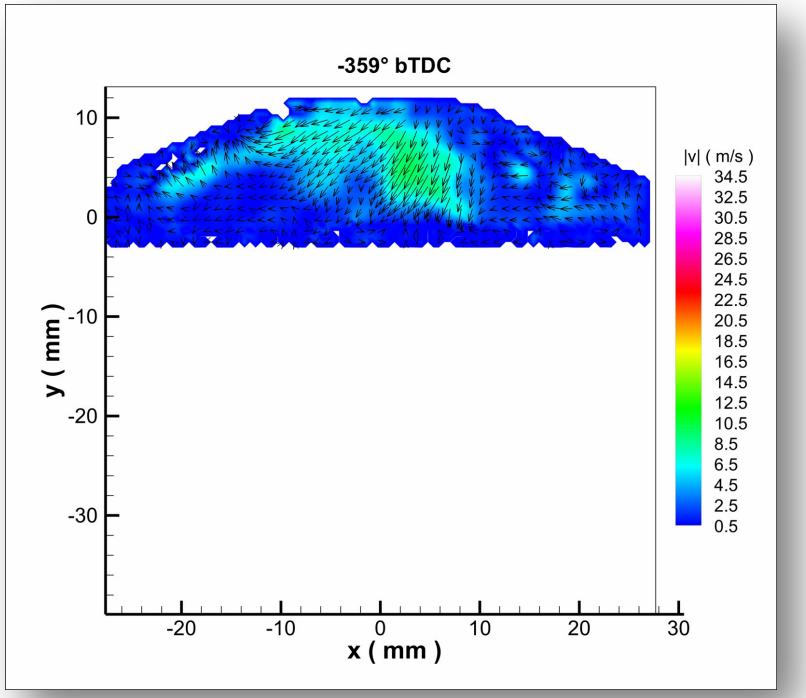
A. Dreizler



Flow field of full IC engine cycle
@ 6 kHz 2C-PIV

Contents

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- Motivation for 4D-imaging
- Scanners
- Fixed multiple sheets
- Tomographic LIF

Motivation for 4D-imaging

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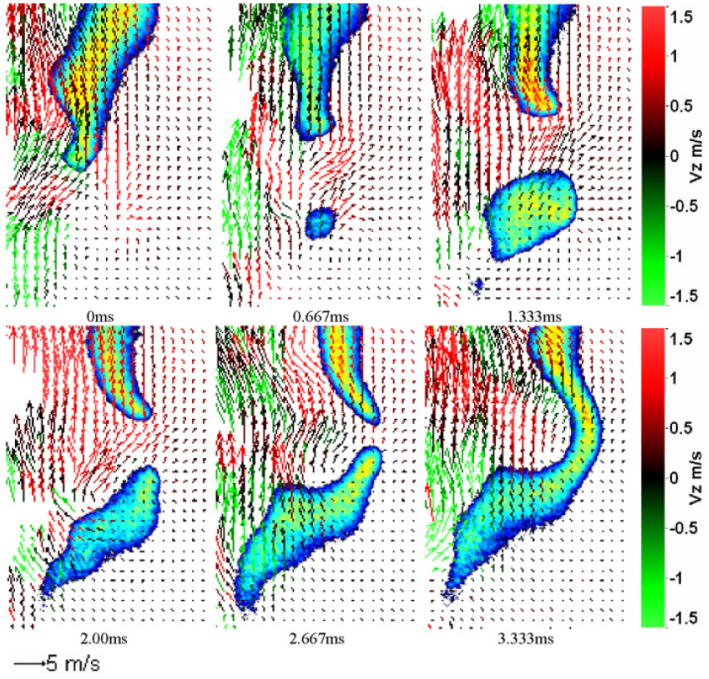
- Turbulent flame are 3D in space and time-dependent
  → 4D diagnostics is a “natural” aim
- Interpretation of 2D-data often ambiguous
- 2D-plane not necessarily representative for observations
- …

Lifted jet flame investigated by planar diagnostics:

Isolated flame islands or connected flame??

PCI 32, 2009, Gordon et al.



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Towards 4D-diagnostics – previous work

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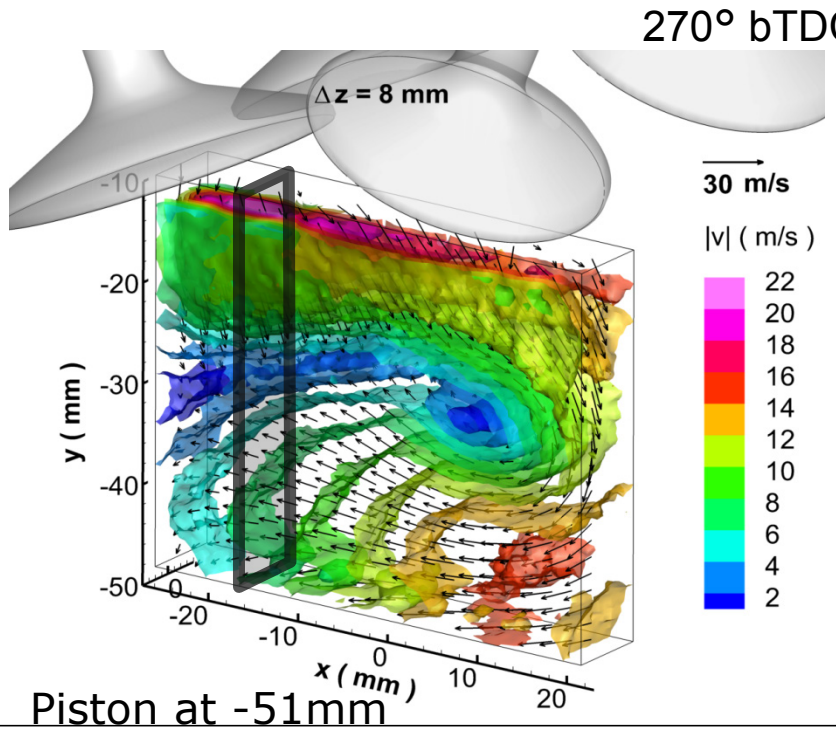
- Flow field (3D-3C) – not discussed here
  - Tomo PIV: volumetric reconstruction of seeding particles (Elsinga, Scarano et al.)
  - Holographic PIV: holographic reconstruction of time-dependent particle positions
  - Shake-the-box: DLR/LaVision-cinematographic volumetric particle tracking

Tomo PIV in IC engine
PCI34, 2013, Baum et al.



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Towards 4D-diagnostics – previous work

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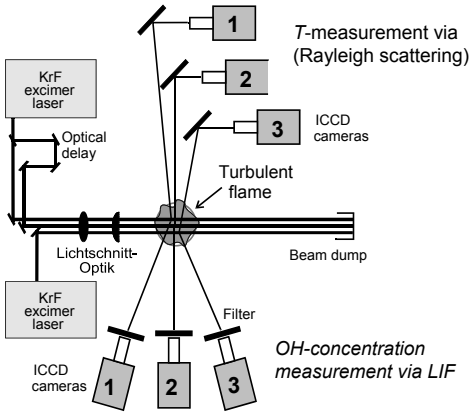
- Scalar field
  - **Challenge**: Continuous spatial distribution instead of disperse particle locations in particle-based velocimetry
  - Method 1: crossed PLIF sheets → 3D information along a line (Barlow et al.)
  - Method 2: quasi-3D by parallel PLIF sheets
    - Scanning of a pulse sequence (Hanson et al., Long et al., Alden et al., Dreizler et al.)
    - Use of different lasers w/o scanning (Wolfrum et al., Dreizler et al.)
  - Method 3: tomographic reconstruction using absorption/emission spectroscopy, needs many projections (

    → limited data tomograph

    Wagner&Dreizler et al. and many others)



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Quasi-4D-diagnostics – flow visualization

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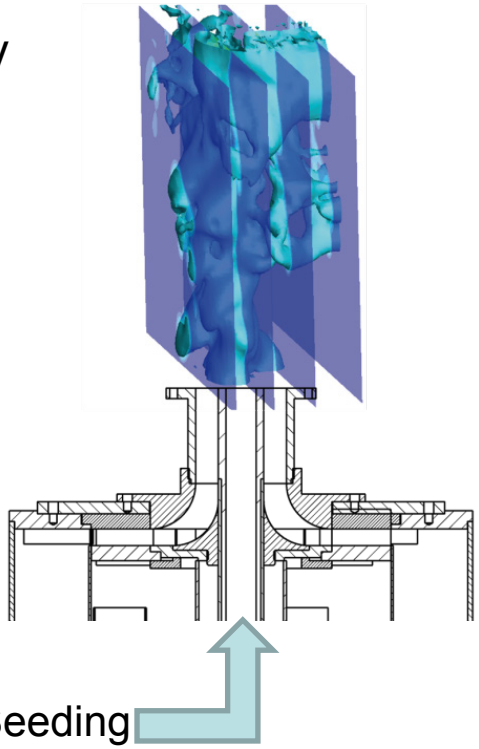
- Mie-Scattering Experiments with modified swirl burner
  - Bluff-body replaced by seeding tube

  → Central jet surrounded by swirled unseeded coflow
  - Isothermal flow
  - Parameters varied: Swirl No., Re No., seeding density

- Sweeping of light sheet by Galvo scan mirror
  - Scan Rate up to 2.5 kHz → suitable for low Re-No.
  - Scanning volume approx. 50x50x50 mm (max)



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Experimental setup

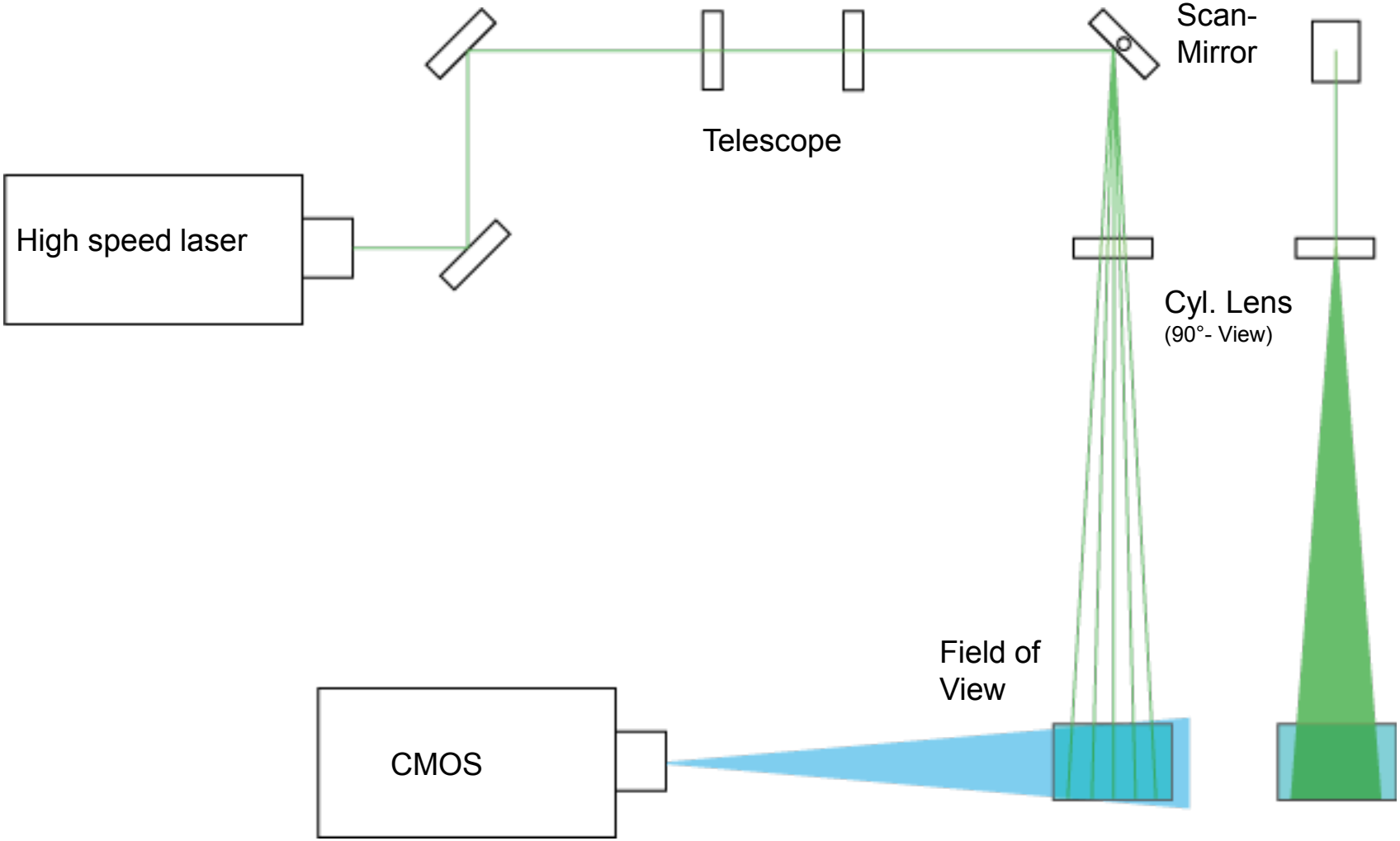
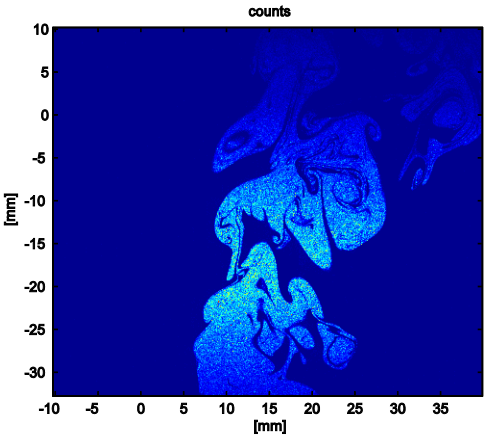
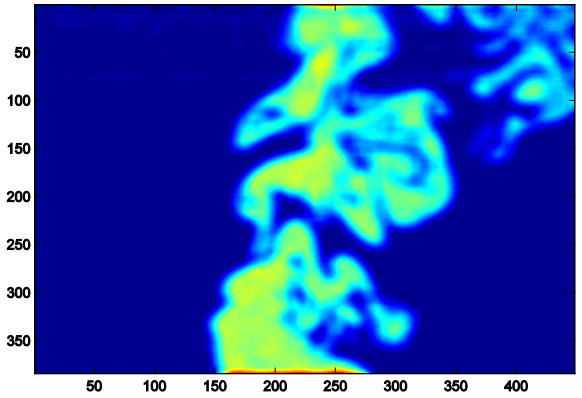


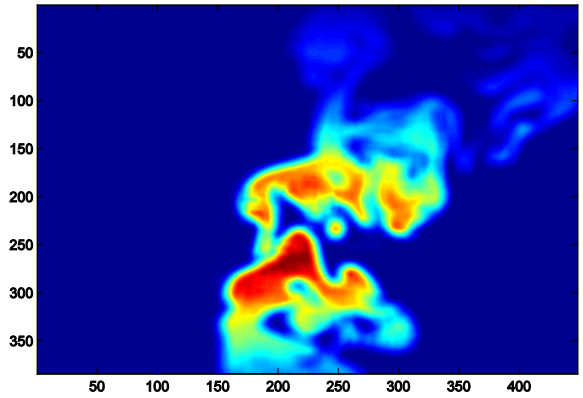
Image post-processing



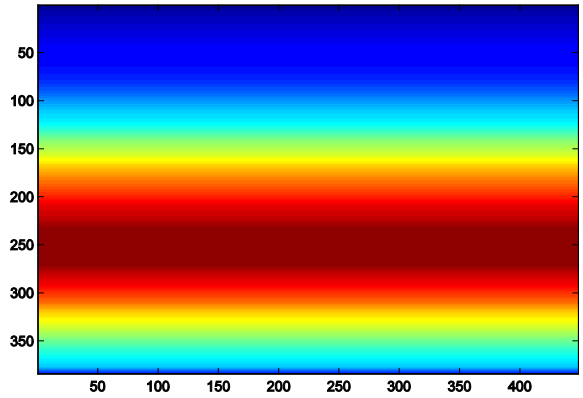
Original Image



Gauß-, Medianfilter



Laser Beam Profile



Results for low Reynolds numbers

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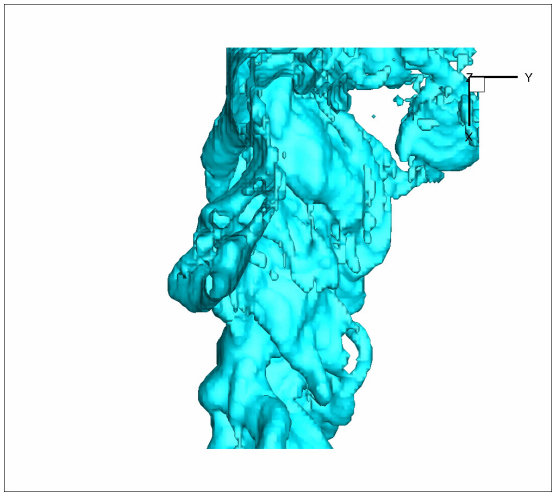
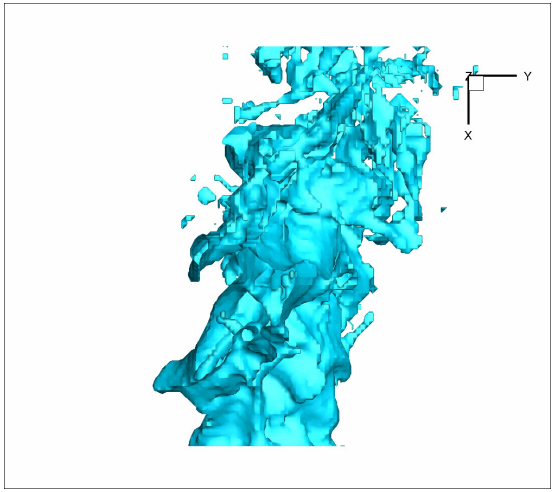
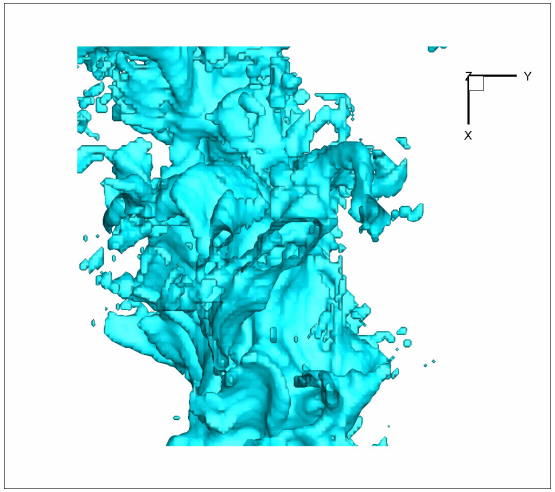
Low speed scanning: 250 Hz
Laser repetition rate: 30 kHz
→ **60** planes/"instant (**2ms**)"

Field of view ~ **50x50x50**mm
Jet: 3800 l/h Re ~ 1000
Annulus: 800 l/h Re ~ 800







0% Swirl ($S_{geo} = 0$) 50% Swirl ($S_{geo} \approx 1$) 100% Swirl ($S_{geo} \approx 2$)

⟹ Increasing swirl breaks up core flow faster

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Results for intermediate Reynolds numbers

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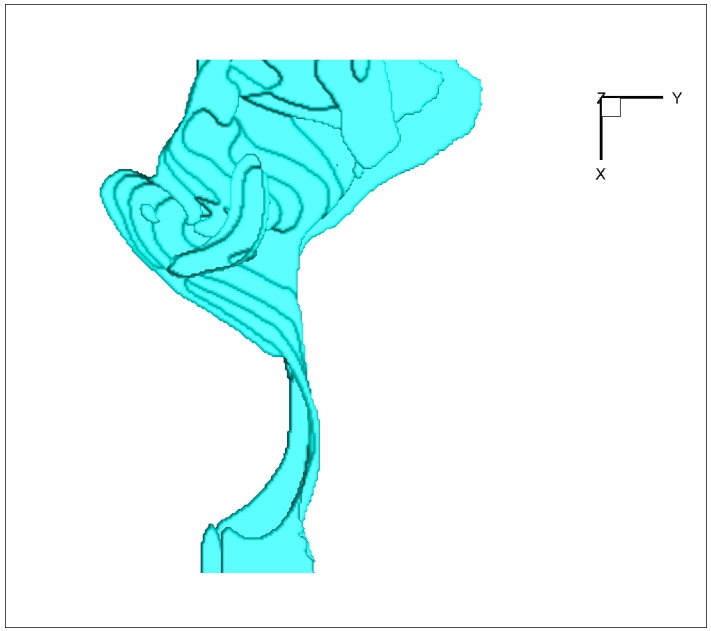
High speed scanning: 2500Hz
Laser repetition rate: 60 kHz
→ **12** planes/"instant (**0.2ms**)"

Field of view ~ **40x40x20mm**
Jet: 17000 l/h Re ~ 4700
Annulus: 1700 l/h Re ~ 1700



0% Swirl

→ **Need for higher scanning rates**

⟹ Spatial resolution too low due to „low" repetition rate
Better reconstruction algorithms required

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Laser Scanning Multiplane Flamefront Imaging

Master Thesis
Max Greifenstein

TECHNISCHE UNIVERSITÄT DARMSTADT

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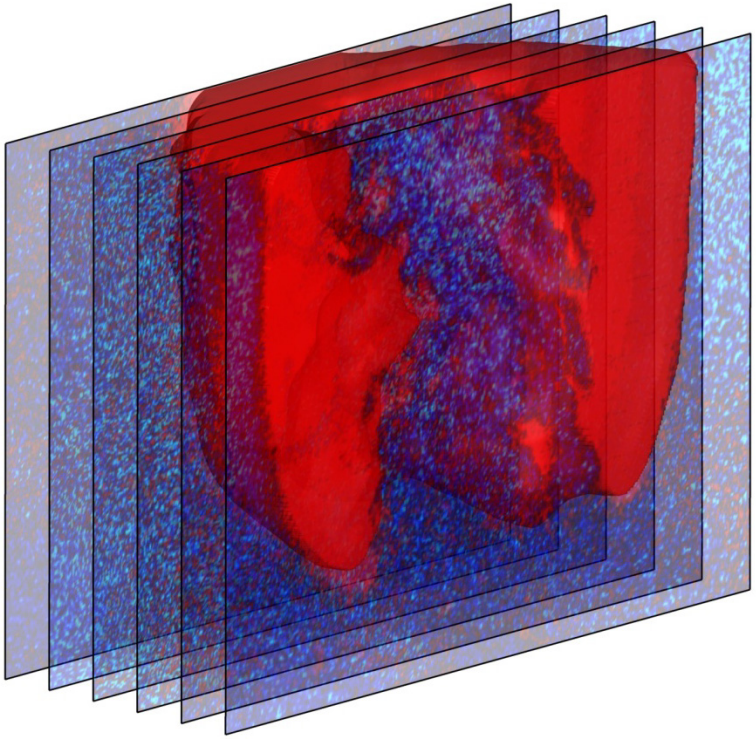

For more details see:
M. Greifenstein et al.
MST 26 (2015)105201

Polygon-Scanning: achieving higher scan rates

f_{Laser}

↕

Spatial resolution

f_{Scan}

↕

Revolution speed,
number of facets

Measuring the Spatial Jitter

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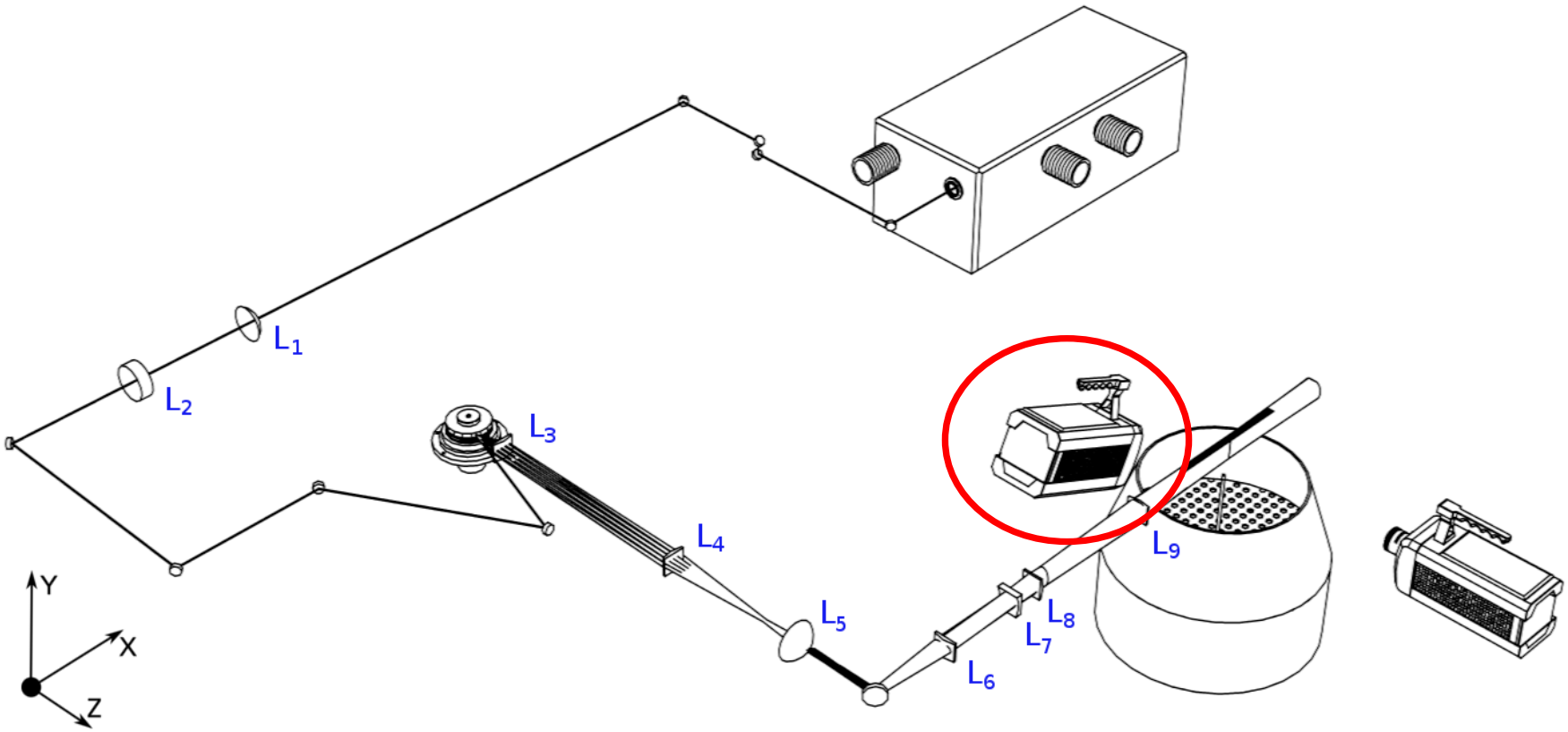

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Spatial Jitter, air atmosphere limits speed to 5 kHz

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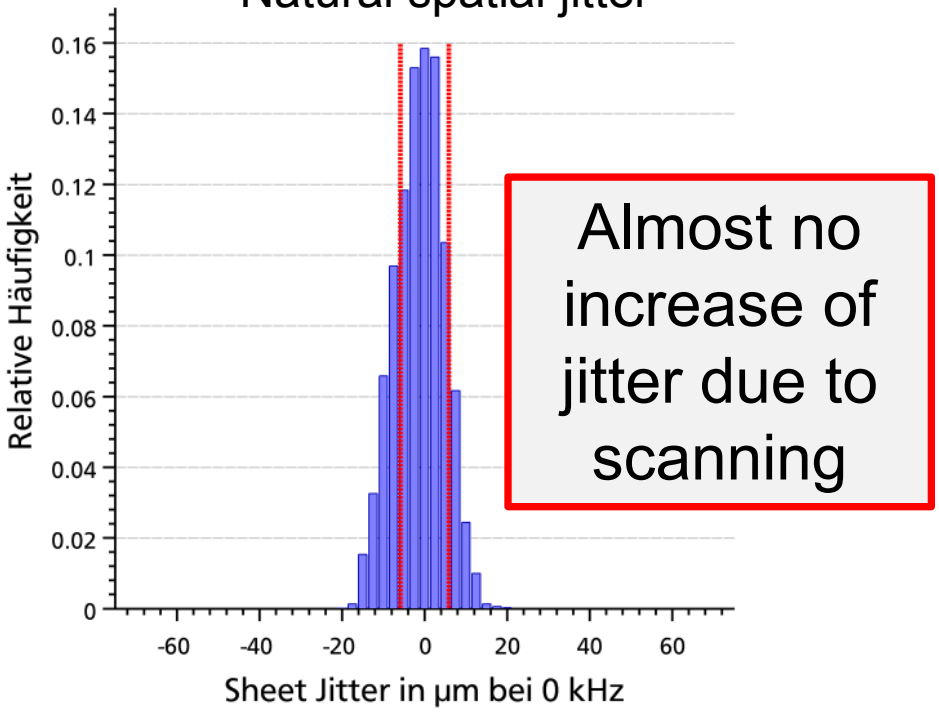
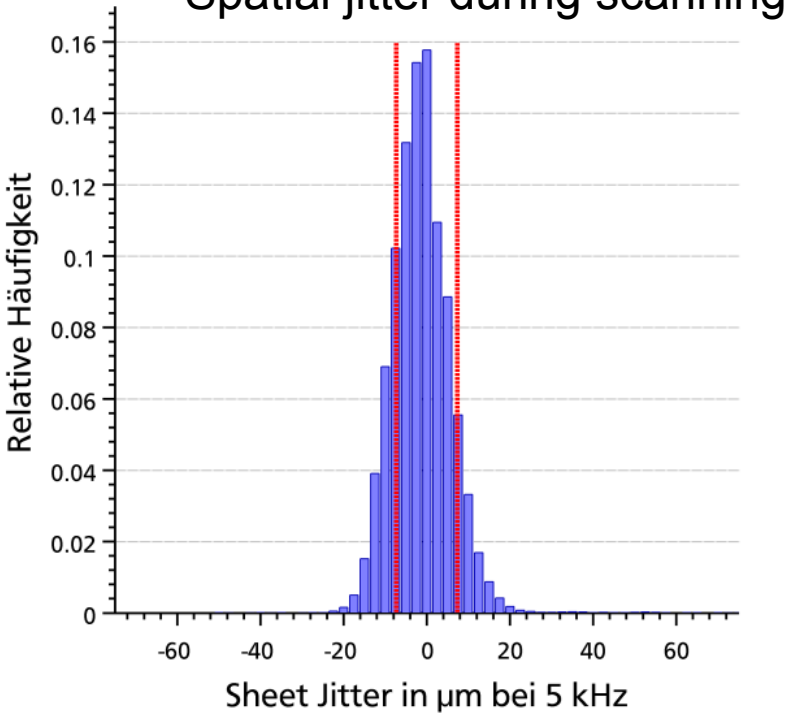
Natural spatial jitter



Almost no increase of jitter due to scanning

Spatial jitter during scanning



0 kHz: $\sigma_{\Delta x} \approx 5.7\ \mu m$
$\Delta z_{max} - \Delta z_{min} \approx 38\ \mu m$

5 kHz: $\sigma_{\Delta x} \approx 6\ \mu m$
$\Delta z_{max} - \Delta z_{min} \approx 40\ \mu m$

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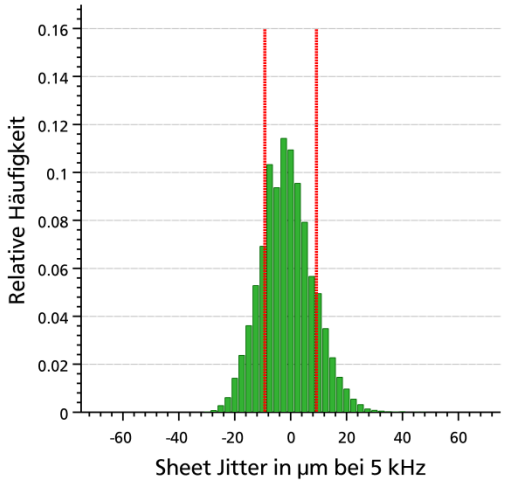
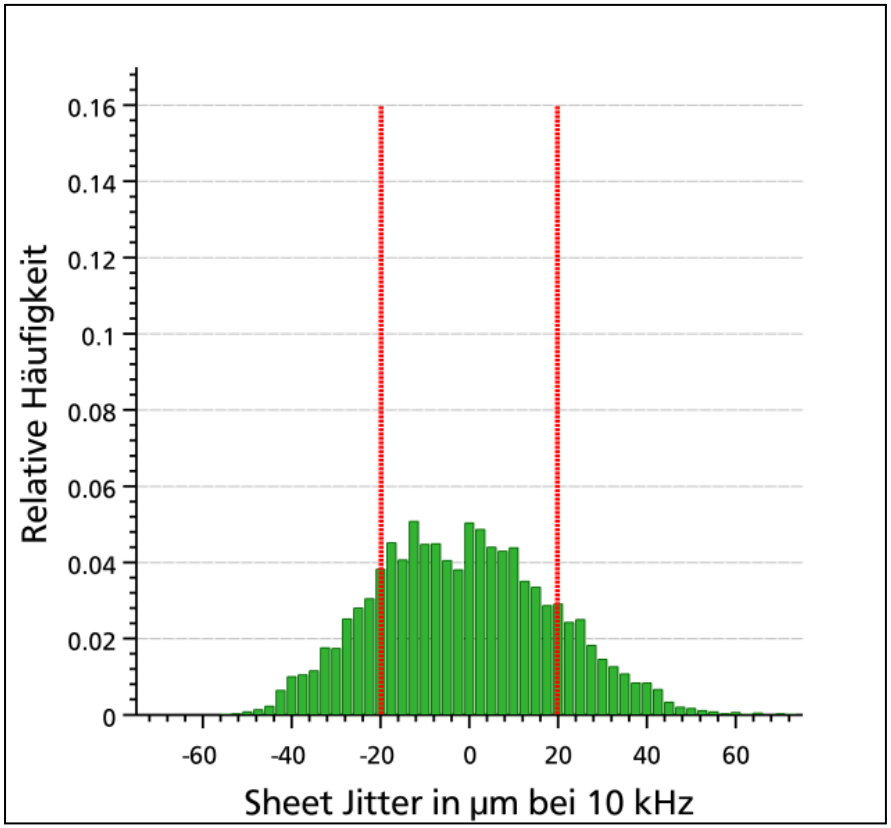
Higher scan rates needs helium atmosphere → reduce frictional losses





→ At 10 kHz increased jitter to $\sigma_{\Delta x} \approx 20\ \mu m$
For optimal performance control parameters need to be adjusted for scan speed

Demonstrating the performance
Target

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- Explore limits of polygon scanning
- Measurements at 2, 5 and 10 kHz scan frequency
- Laser repetition rate (@532 nm): 50 kHz

→ Time-resolved volumetric reconstruction of a turbulent flame front by using Mie scattering off µm-sized particles

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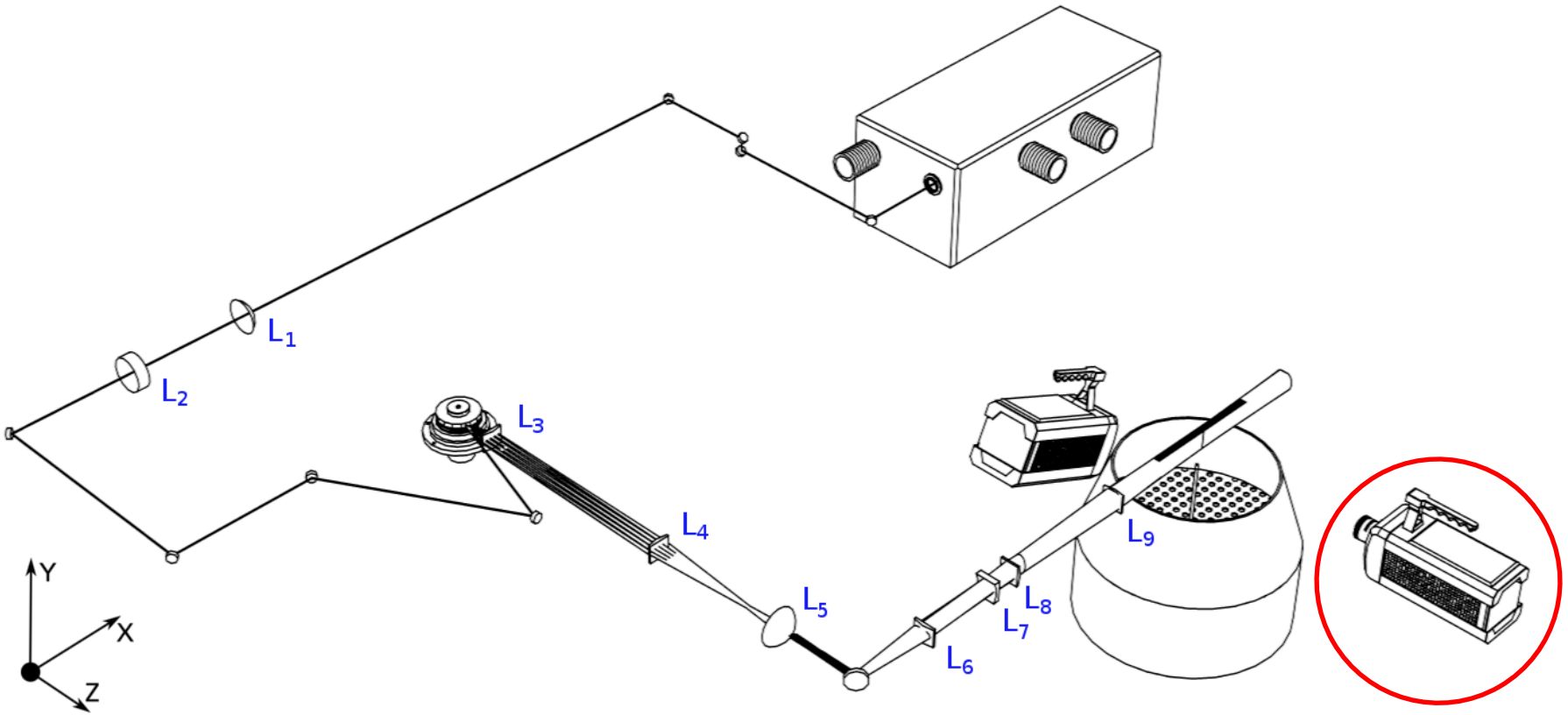
Demonstrating the performance
Beam path



Demonstrating the performance
Lifted turbulent flame

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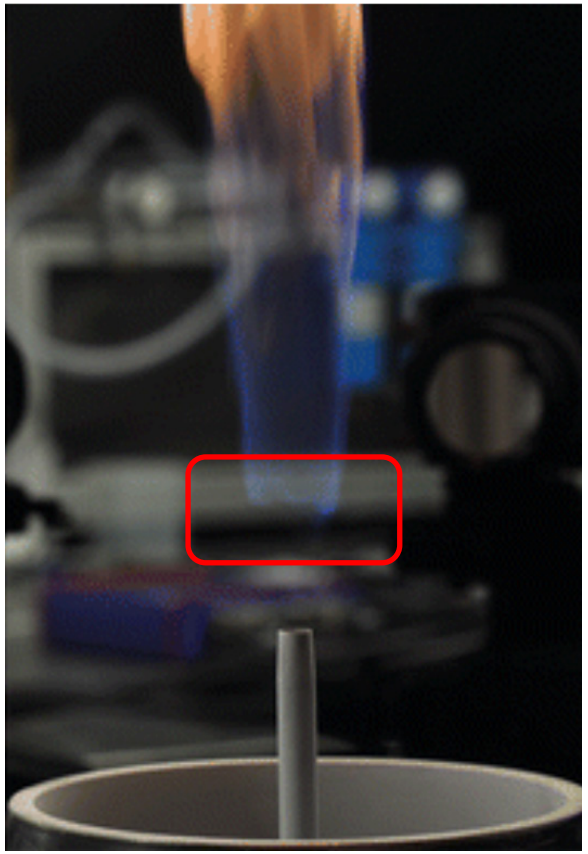
- Lifted jet-flame
- Methane-jet: Re = 5000
- Co-Flow air: Re = 1625
- Seeding: variation used for flame front tracking
  - 1 µm-sized oil droplets
  - Al_2O_3 solid seeding



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Demosntrsting the performance
Calibration

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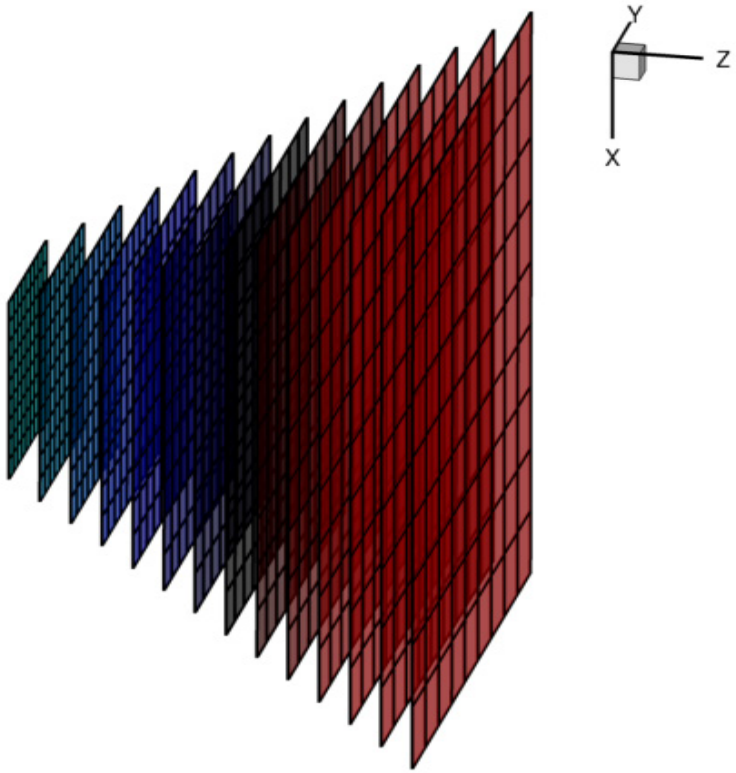
- Type 058-5
  - Point-to-point distance: 5 mm
- Each plane calibrated by traversing

→account for different magnification



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Demonstrating the performance
2D flame front detection

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1. Raw image
2. Normalization
3. Low pass filter
4. Normalization
5. Median filter
6. Low pass filter
7. Normalization
8. Gradient
9. superposition

Demonstrating the performance
Cinematographic and volumetric flame front

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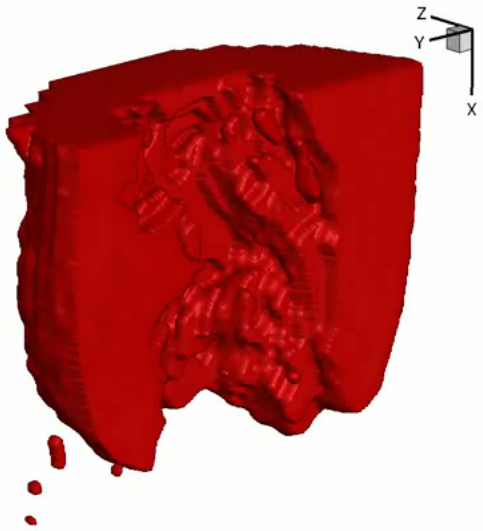
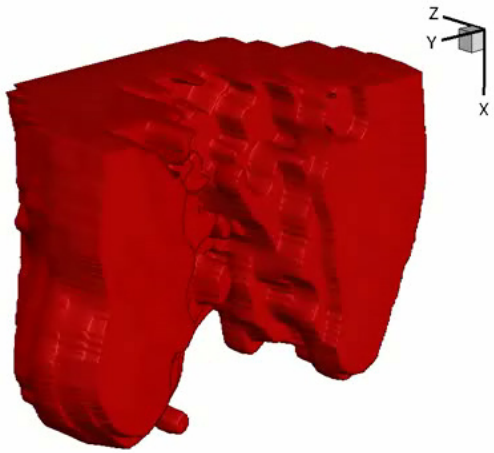
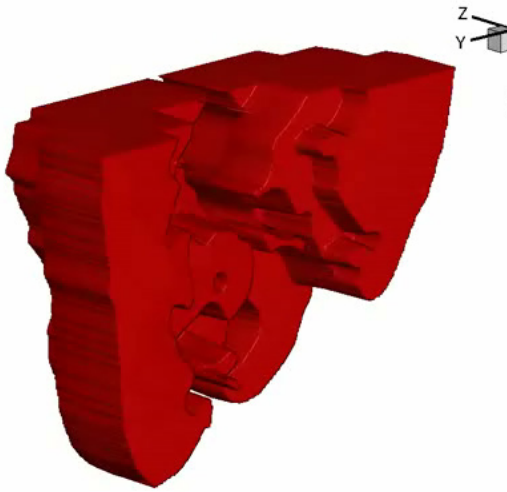
2 kHz



5 kHz



10 kHz



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Demonstrating the performance
temporal resolution and spatial discretization

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In-Plane correlation:

How well correlates one image with following one from next sweep at the same spatial position?

→ Measure for temporal resolution of the scan

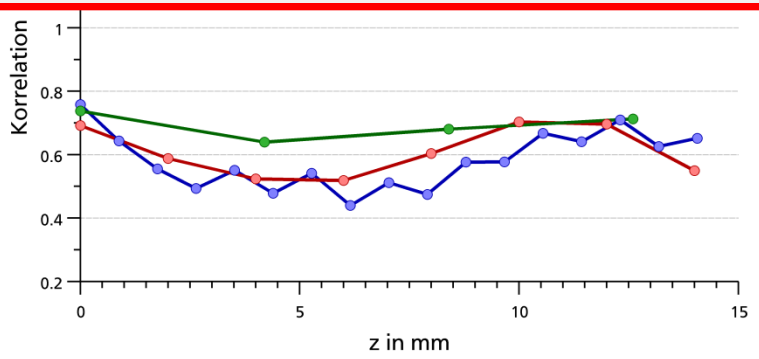
Out-of-Plane correlation:

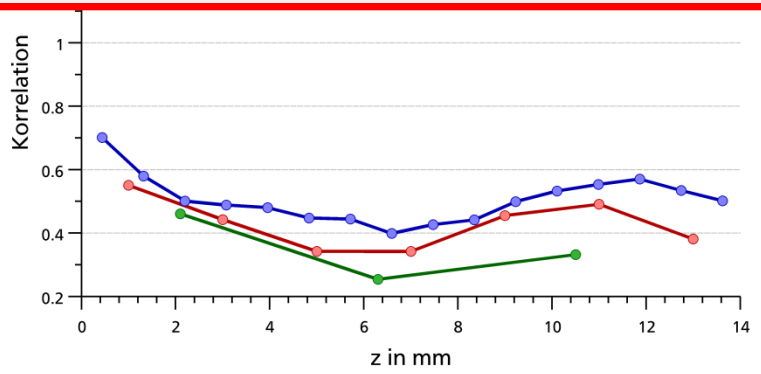
How well correlates one image with the neighbouring ones during one sweep?

→ Measure for the spatial discretisation in scan direction

Raw data!

High scan rate with good temporal resolution comes along with bad out-of-plane discretization





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Demonstrating the performance
Smoothing

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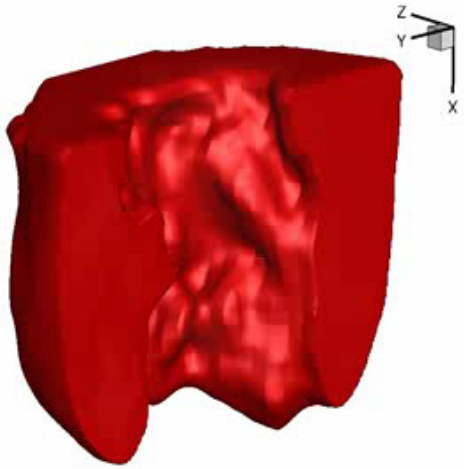
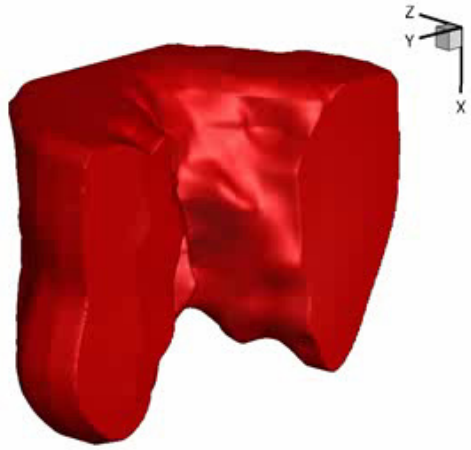
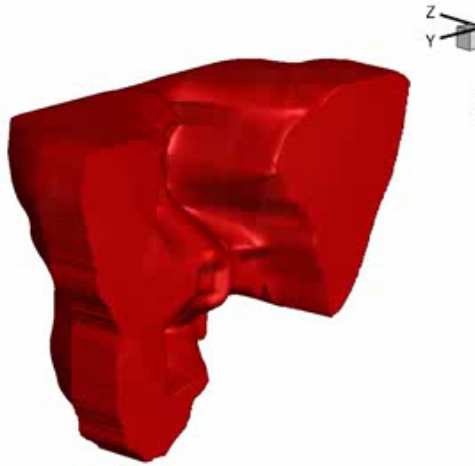
2 kHz



5 kHz



10 kHz



At 10 kHz we lost almost all out-of-plane structures
→ We need higher laser repetition rates!

t = 0 ms

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Demonstrating the perfromance
Results of spatial smoothing

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In-Plane correlation:

How well correlates one image with following one from next sweep at the same spatial position?

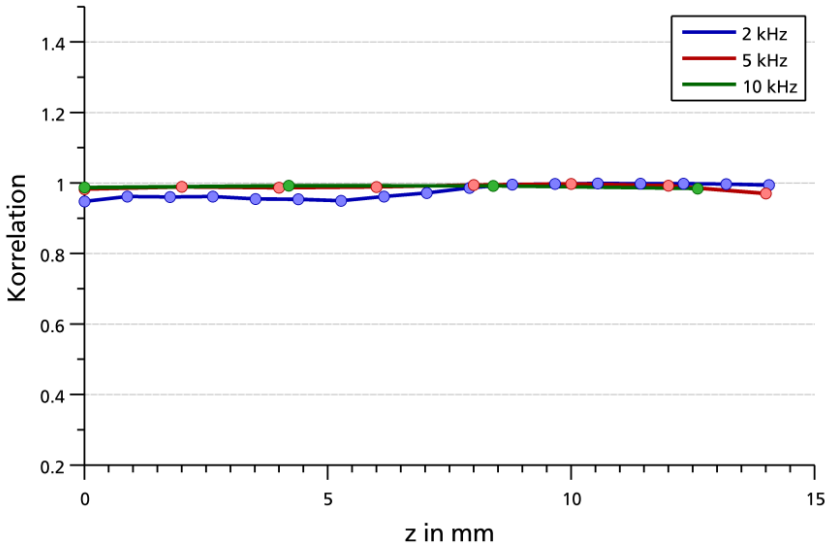
→ Measure for temporal resolution of the scan

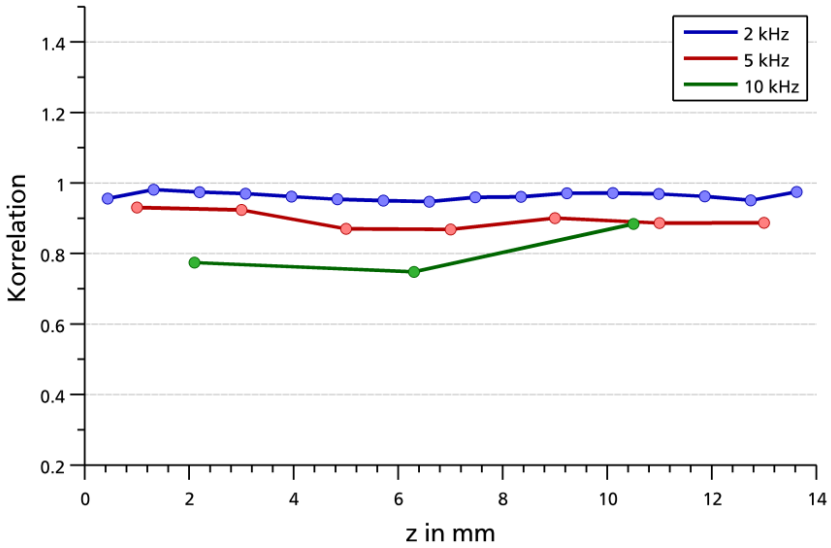
Out-of-Plane correlation:

How well correlates one image with the neighbouring ones during one sweep?

→ Measure for the spatial discretisation in scan direction

Filtered data!





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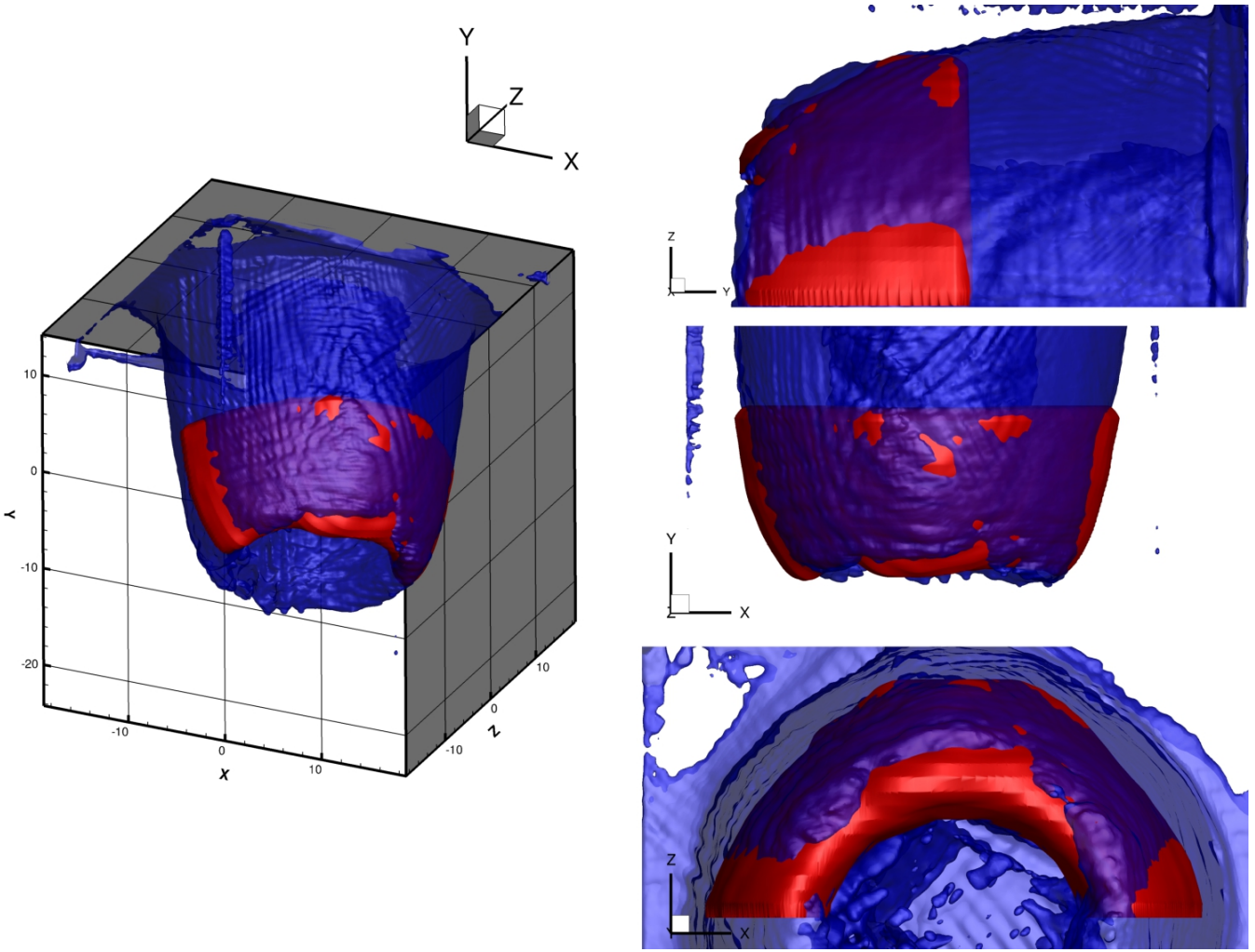
Demonstrating the performance
Mean flame front and mean tomographic chemiluminescence results



Summary polygon scanner performance

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- Sheet-Jitters < 8 µm for 2-5 kHz scan frequency in air
- In helium-atmosphere at 10 kHz scan frequency: ~20 µm

→Compared to commercial galvo-scanners 2-10 times higher scan frequency with lower sheet-jitter

→Find compromise between temporal resolution and spatial discretization

→Need for lasers with higher pulse repetition rate

- Data post-processing of high importance
- Need for proper documentation of procedure used for data post-processing

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Most recent development: Acousto-optic deflector

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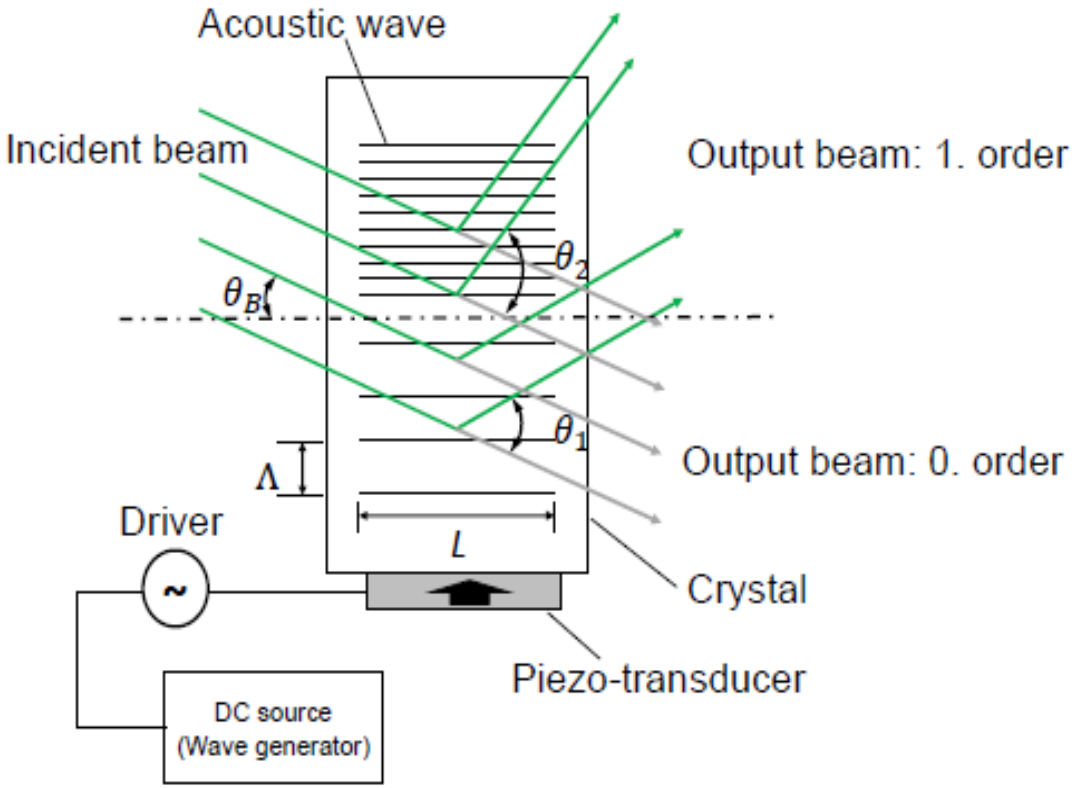
- Faster than any mechanical device
- No moving parts
- Use of Bragg reflection
- Changing acoustic wavelength (frequency) → change of Bragg angle

$$sin\theta_B = \frac{\lambda}{2\Lambda}$$



T. Li et al. Appl. Phys. B 2017

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Dual plane imaging

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Example turbulent flame speed measurements

- Atmospheric pressure: freely propagating flame
- SI IC Engine: early flame propagation

Method developed in collaboration with I. Boxx and W. Meier (DLR-Stuttgart)

PCI 34, 2013, Trunk et al.

DLR

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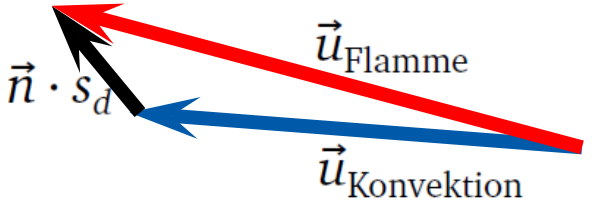
Premixed flame propagation – background

- Turbulent flame speed ($\vec{n} \cdot s_T$) is a key-quantity: determines rate of fuel consumption
- 3D in nature → needs multi-parameter + temporally resolved quasi-3D measurement techniques
- Background:

$$\vec{u}_{flame} = \vec{u}_{displacement} + \vec{u}_{convection}$$
$$= \vec{n} \cdot s_T + \vec{u}_{convection}$$
$$\vec{n} \cdot s_T = \vec{u}_{flame} - \vec{u}_{convection}$$



Turbulent displacement speed

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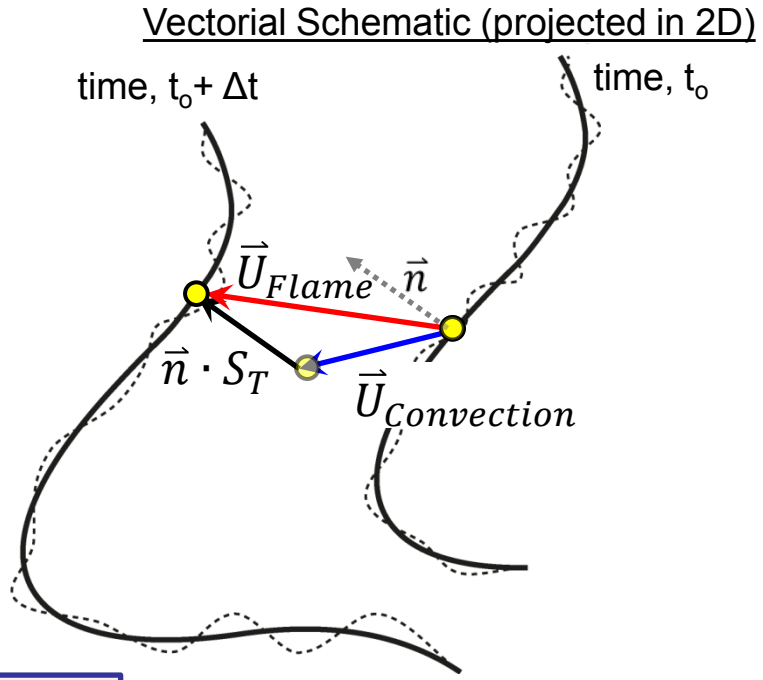
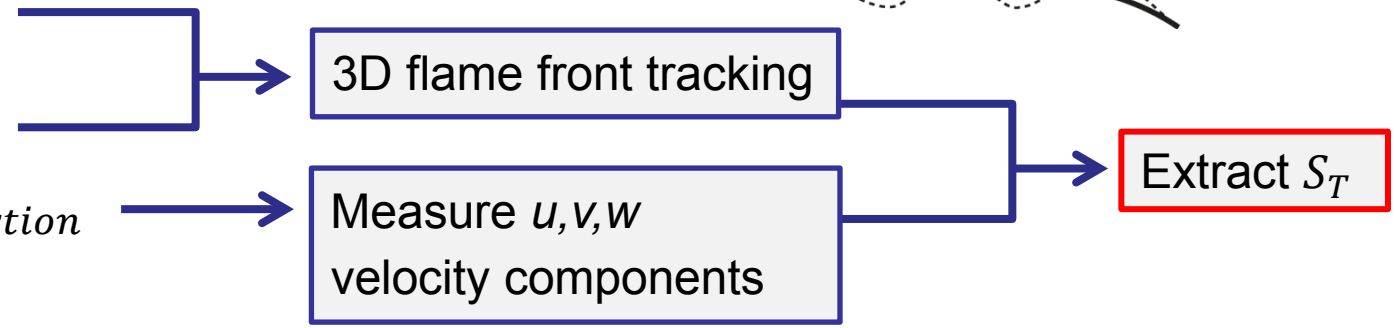
- Absolute flame displacement
  - $\vec{U}_{Flame} = \vec{n} \cdot S_T + \vec{U}_{Convection}$

    $\underbrace{\vec{n} \cdot S_T}_{\text{Flame speed}} = \vec{U}_{Flame} - \vec{U}_{Convection}$

- 3-dimensional in nature

- How to resolve quantities?
  - $\vec{n}$
  - $\vec{U}_{Flame}$
  - $\vec{U}_{Convection}$





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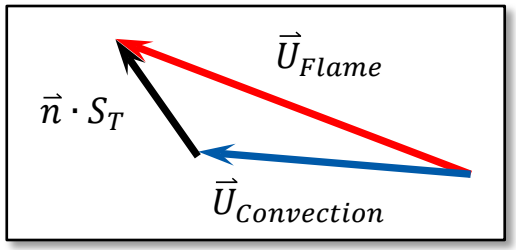
Turbulent flame speed during early flame dev.



Stereo PIV: **Volume PIV:** **flame front tracking**:

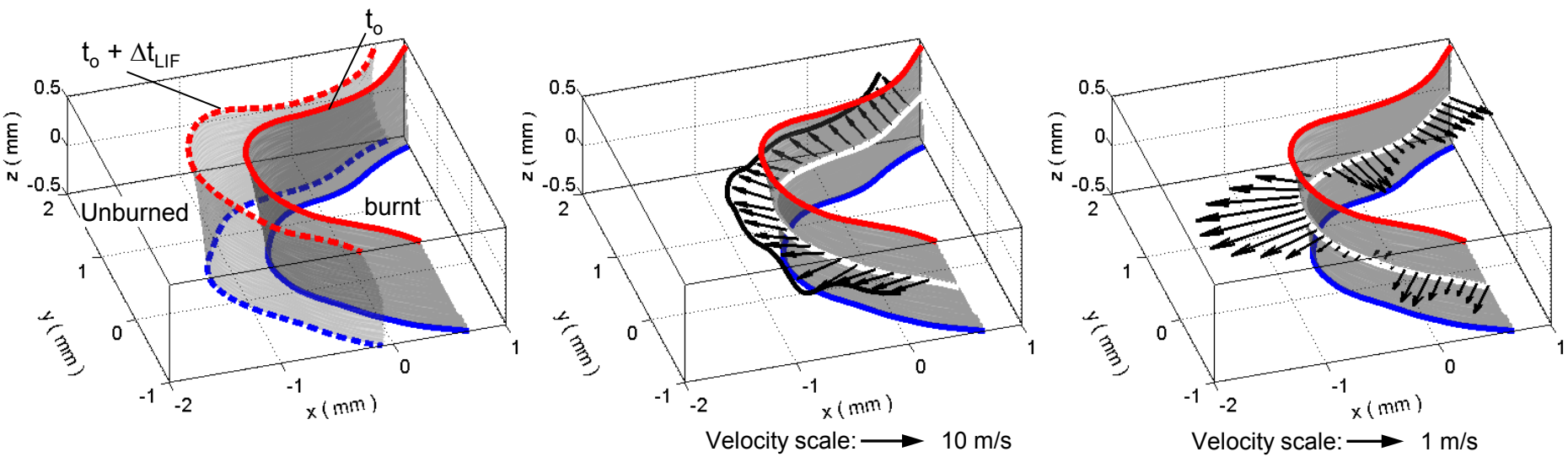
OH-PLIF in two parallel planes

Sandwiched between OH-PLIF planes

Flame Surfaces:
Reconstructed from 2 planes

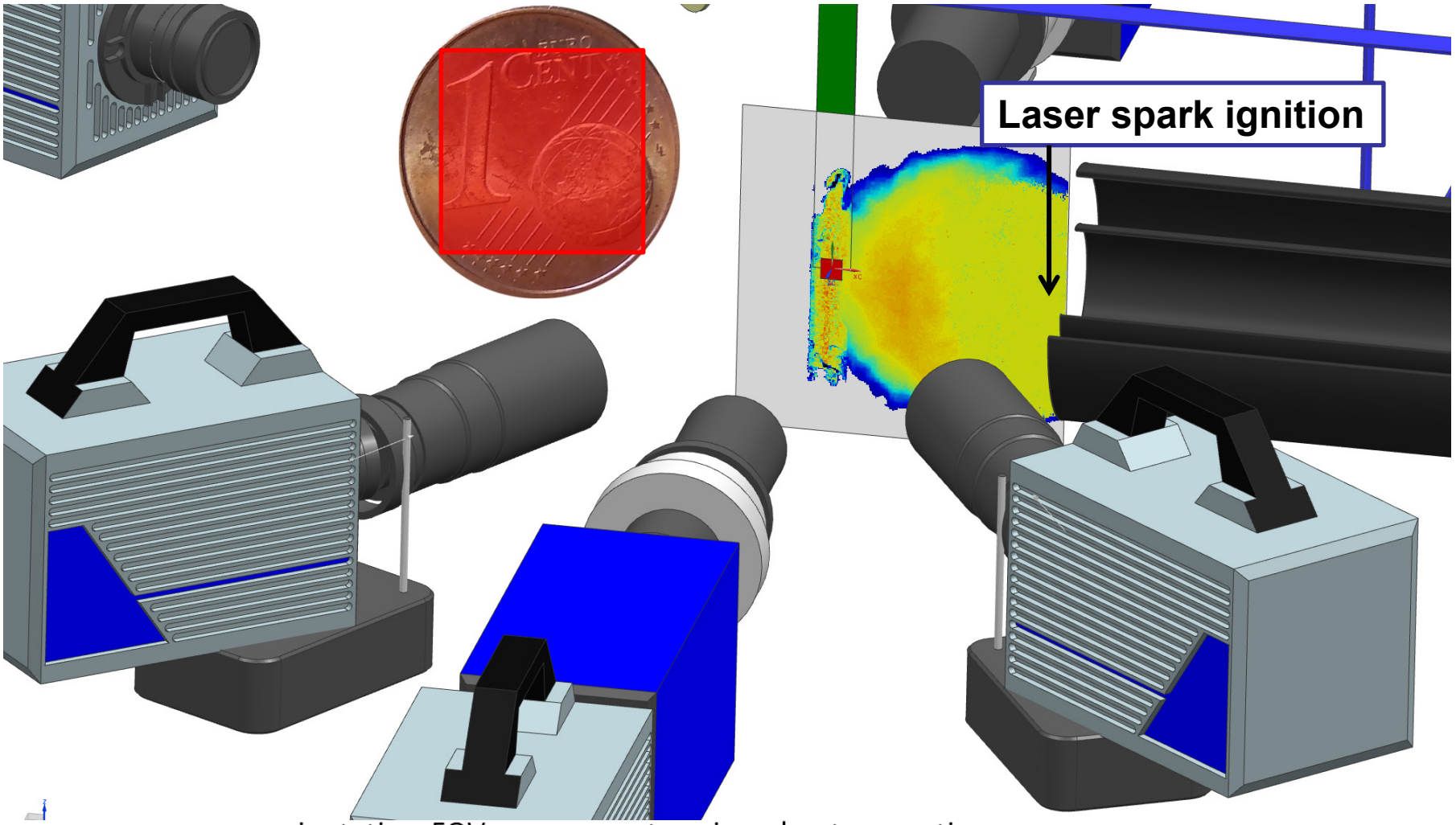
Conv. vel. 0.4 mm from surface

Flame speed in normal direction



$\vec{U}_{Flame}$ $\vec{U}_{Convection}$ $\vec{n} \cdot S_T$

Premixed flame propagation – exp. setup



Method – *Configuration*

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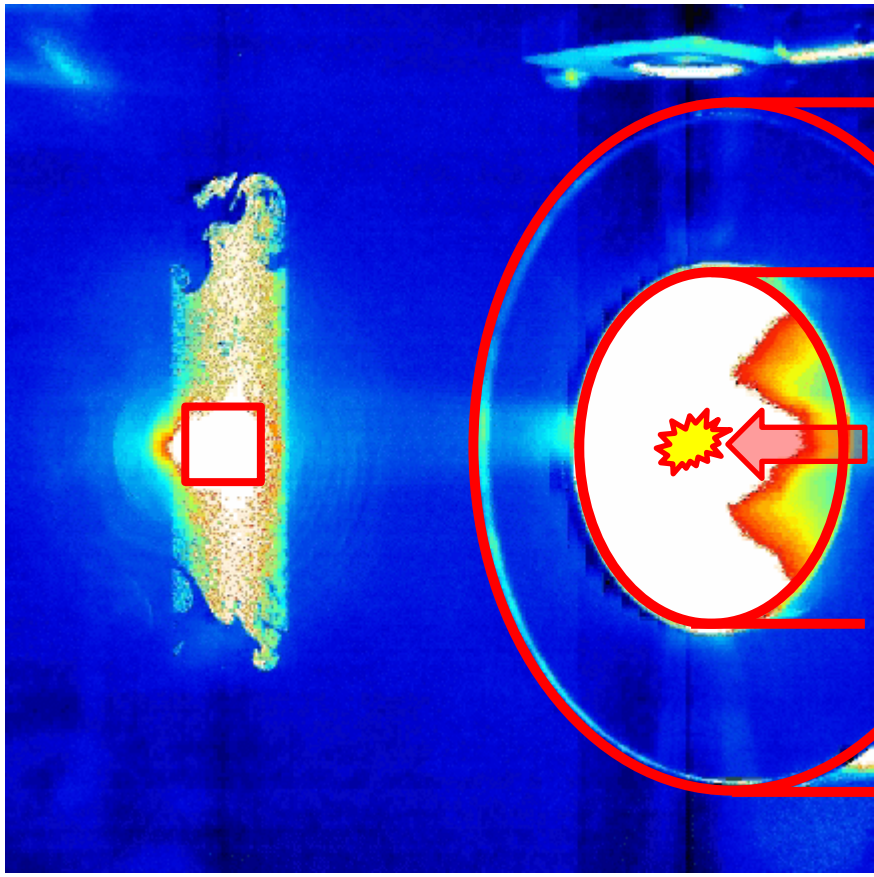
- **Flow Facility and Flame Configuration**

fuel	methane - air
Re	10000
Φ	1
d	85 mm
U_0	1.81 m/s
Integral length scale	ca. 40 mm
Kolmogorov scale	0.26 mm
coflow	no shear
measurment location	160 mm (2d)upstream
Re_t	90
FOV	12 x 12 mm



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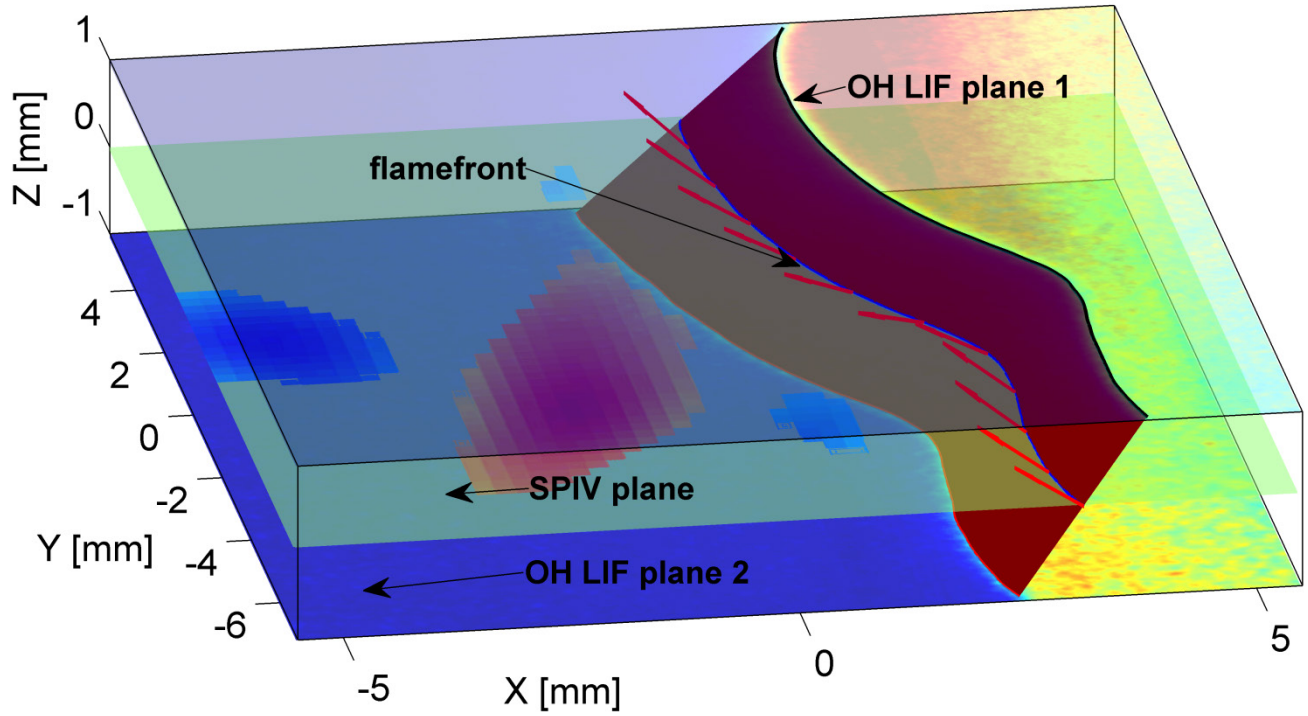
Visualization of flame surface in 3D space



+ information on temporal development → displacement speed

Temporal sequence of flame sequence

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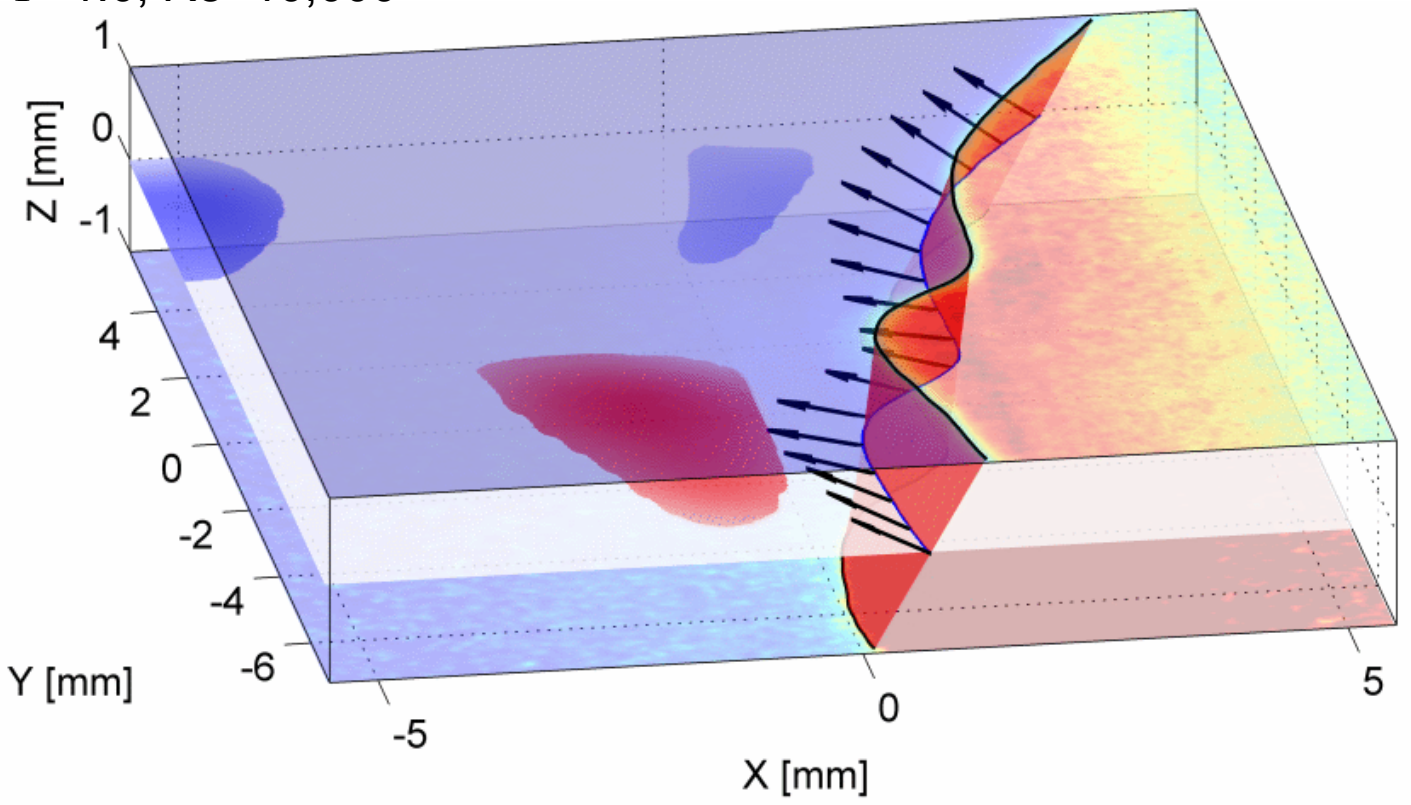
CH_4/air, Φ=1.0, Re=10,000



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Single Shots

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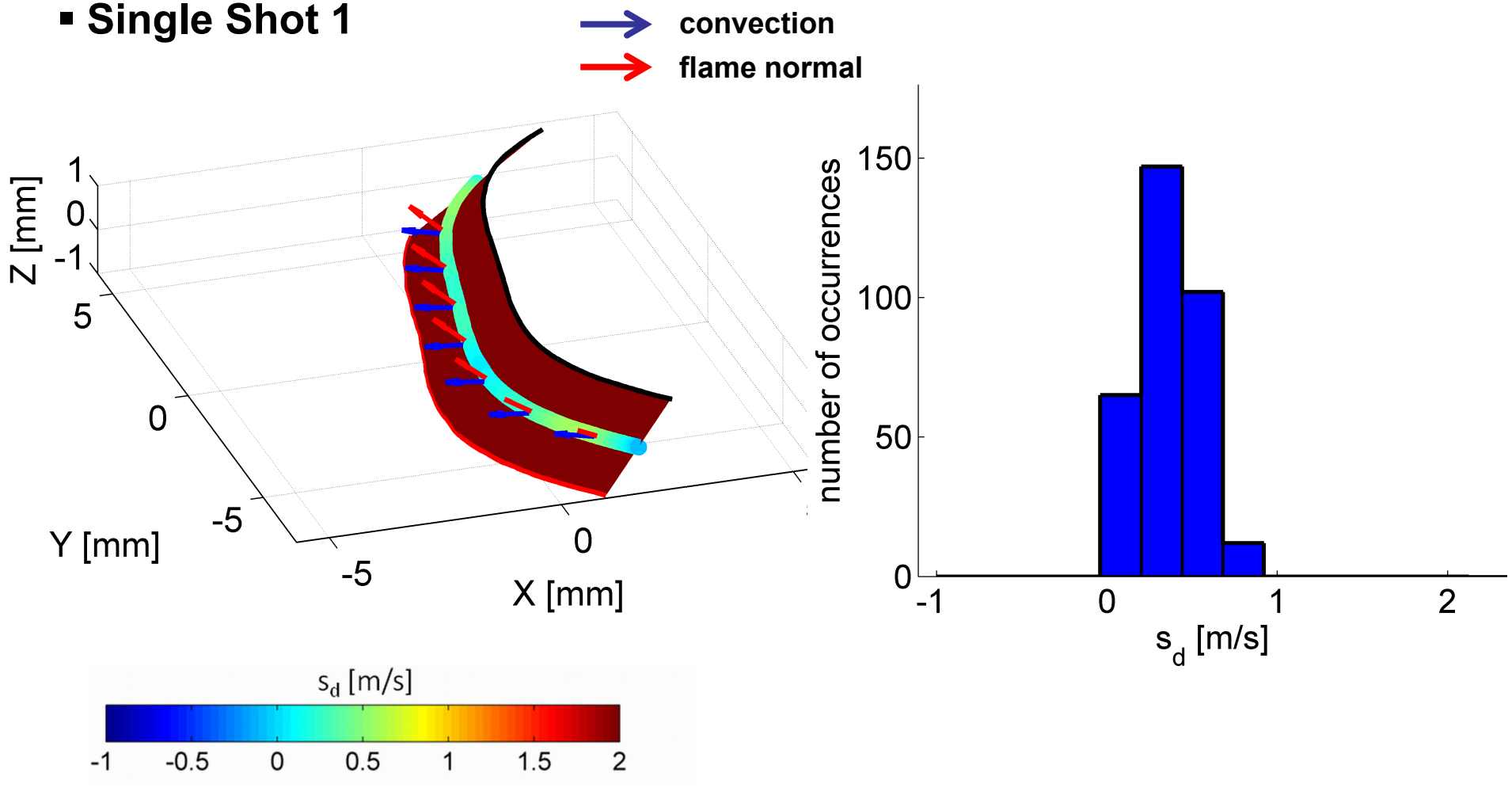
- **Single Shot 1**



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Single Shots

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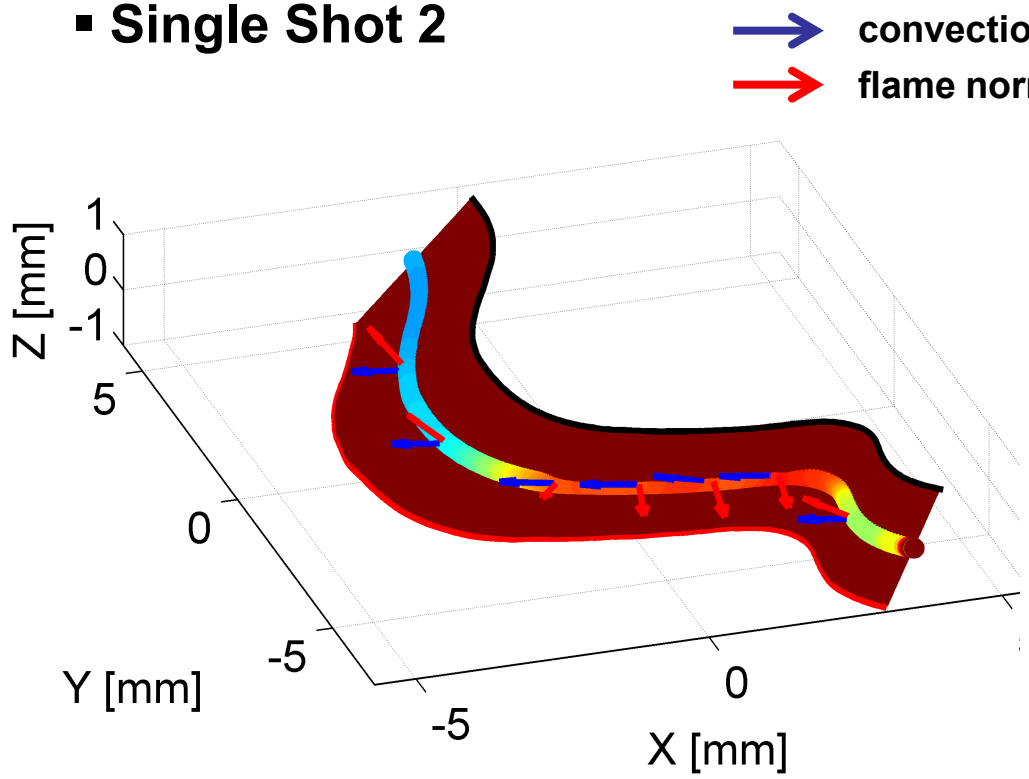
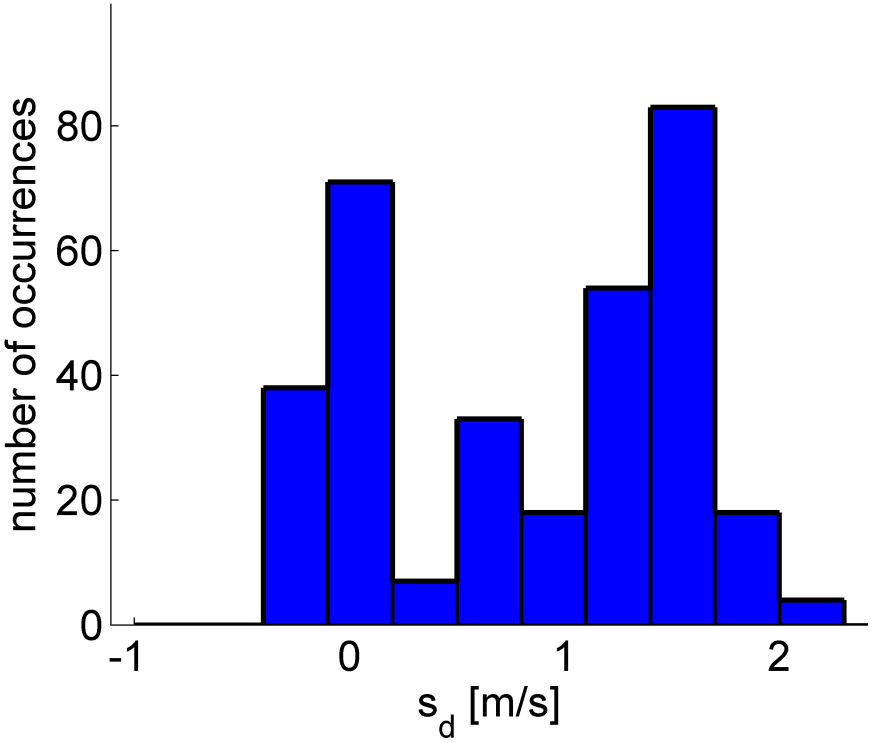
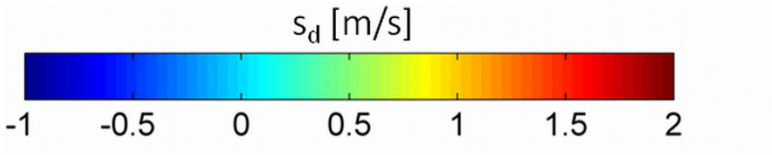
- **Single Shot 2**







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Single Shots

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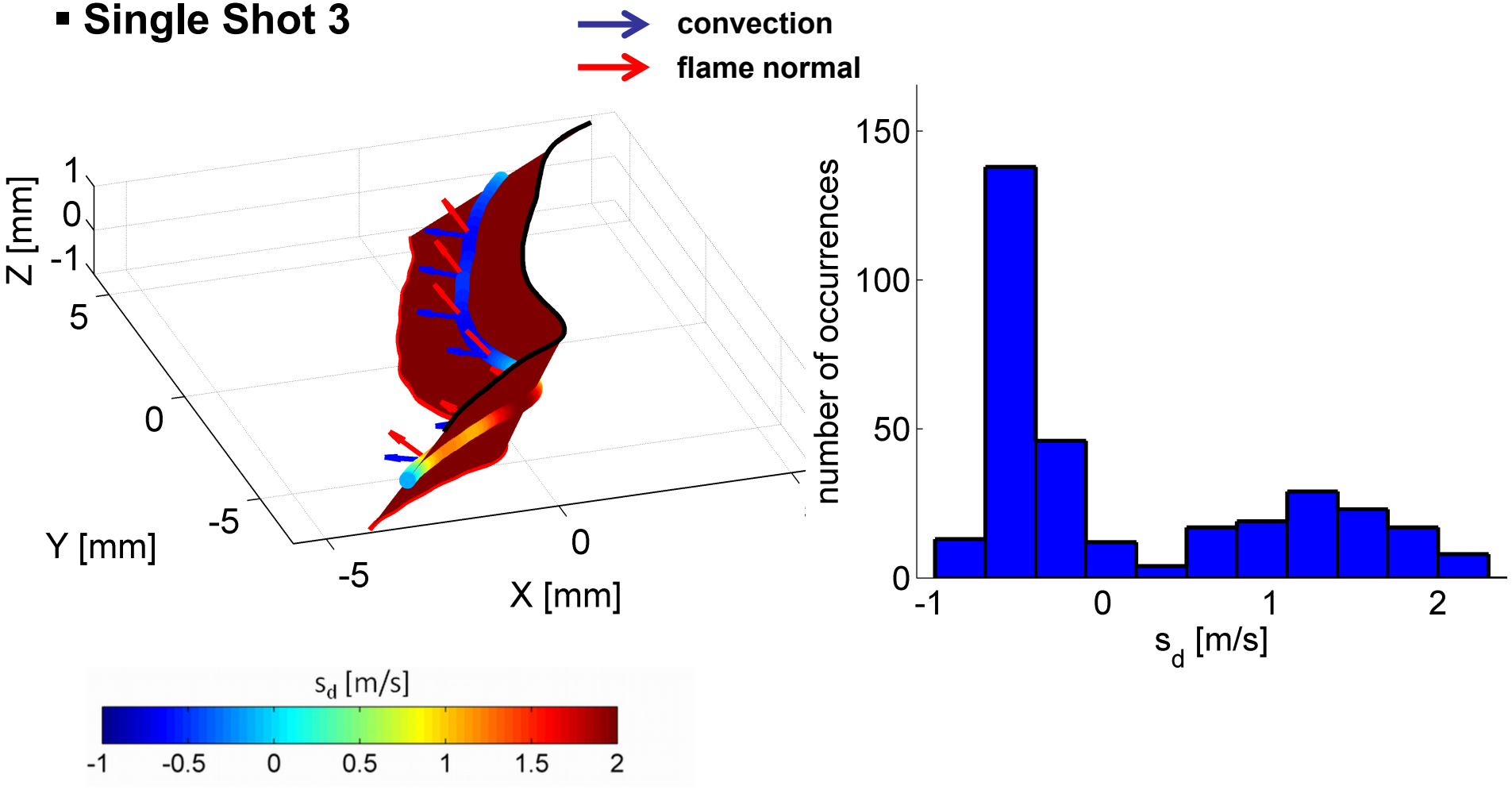
- **Single Shot 3**



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Displacement speed statistics

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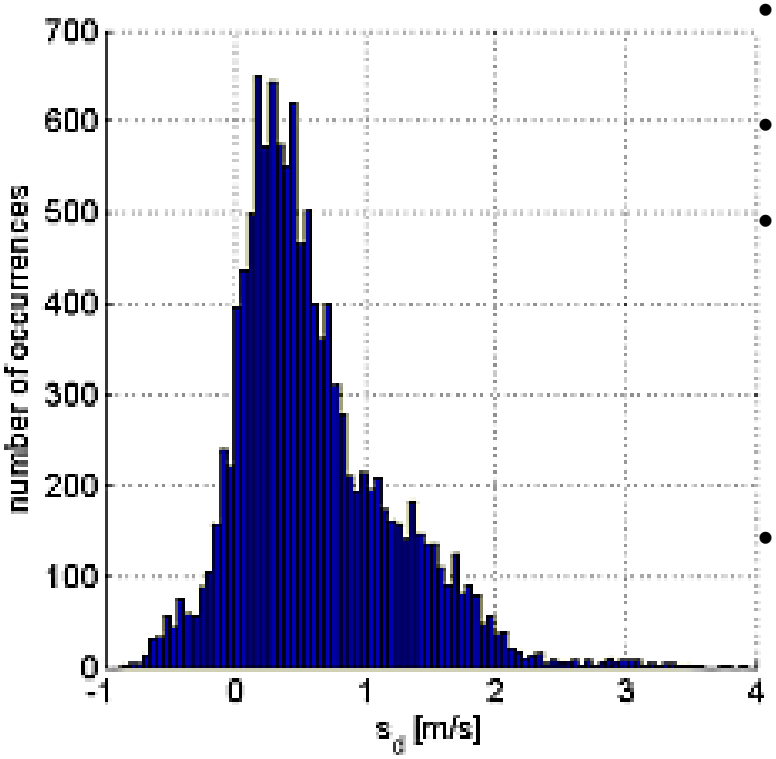
- **Displacement speed statistics (CH_4/air; ϕ = 1.0)**



- Histogram centered around 0.35 m/s
- also higher displacement velocities up to 8 x s_L
- small parts show negative displacement velocity
  - → thermo-diffusive effects
  - → changes in flame structure not accounted for in turbulent combustion models
- can also be found in numerical work:
  - ➢ Gran & Chen 1996
  - ➢ Bilger & Kim 2005

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Transfer to IC engine: Early flame propagation in SI-IC-engine

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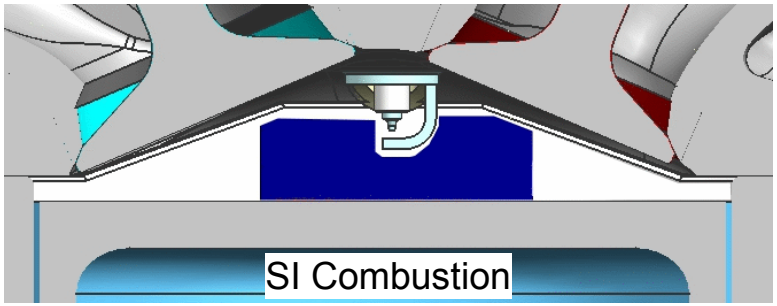
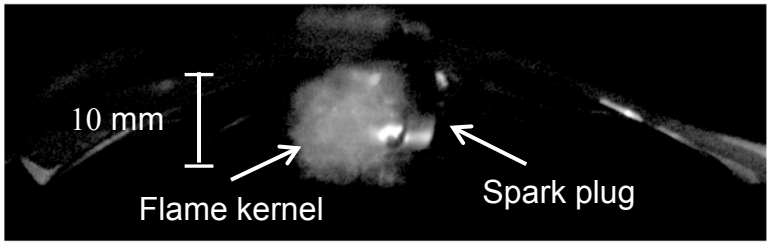
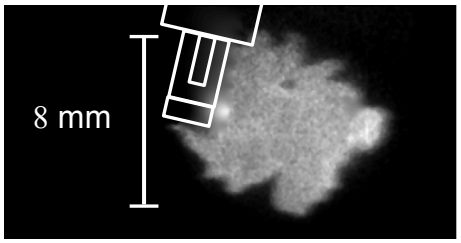
- Early flame development, less than 5% burned mass
- Issue here:
  1. Influence of turbulence on local **flame displacement speed**
  2. Cyclic variations



Mie scattering, evaporating oil drops



Chemiluminescence imaging



OH-LIF imaging

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Experimental setup

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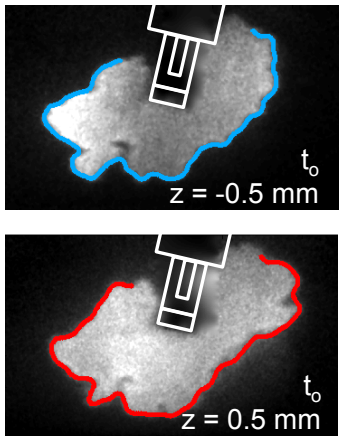
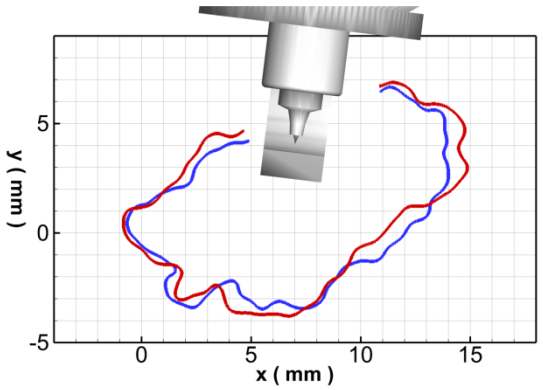
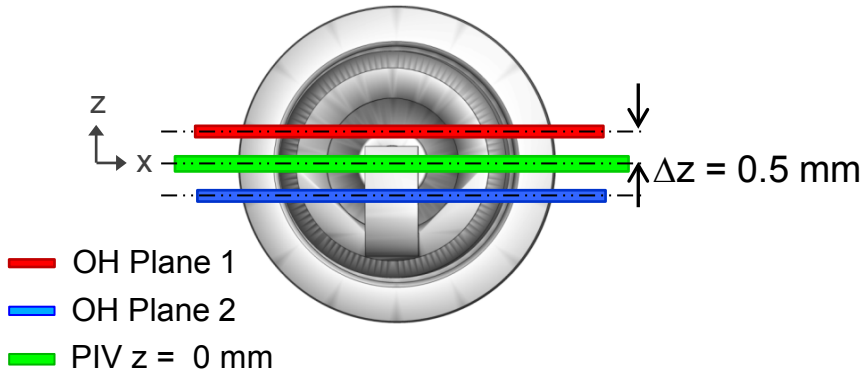
- Dual-plane OH-LIF
  - Two independent UV laser systems (double-pulsed)
  - OH LIF images in parallel planes
- SPIV
  - Central tumble plane

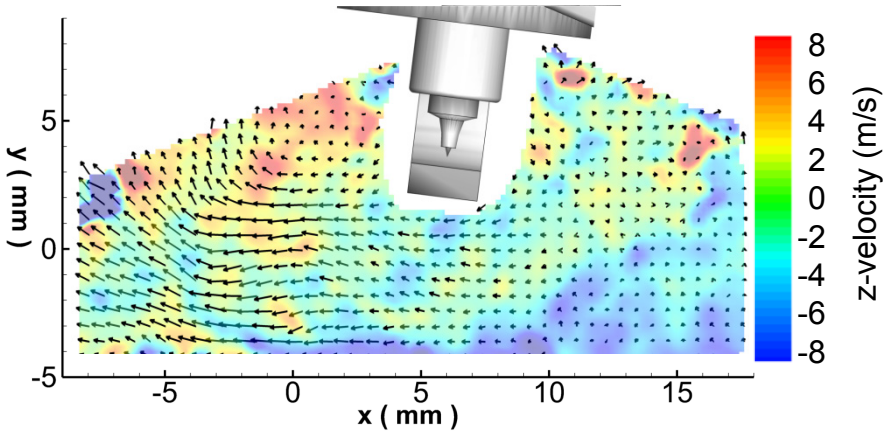
Dual-plane OH-LIF







Stereoscopic PIV



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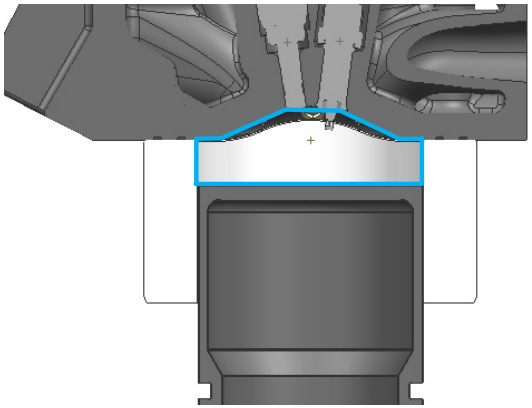
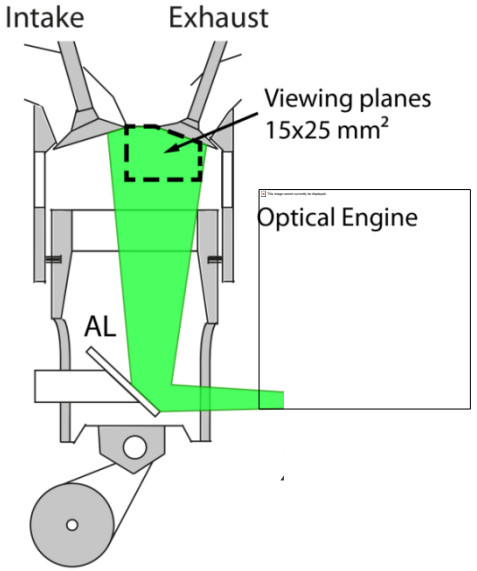
Operating conditions

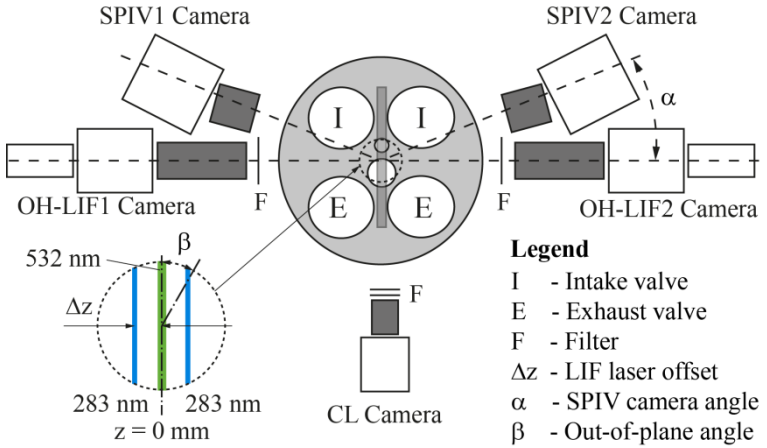
- 800 RPM
- Iso-octane, air, λ= 1
  - Port-fuel, homogeneous
- Intake: P = 0.95 bar, T = 295 K
- Spark 19° bTDC

- HS-PIV, Chemiluminescence
- 4 shot OH-LIF (2 shots each plane, Δt = 50μs) @ 14°bTDC

- Spray-guided cylinder head







Turbulent flame speed during early flame dev.

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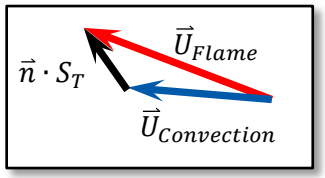
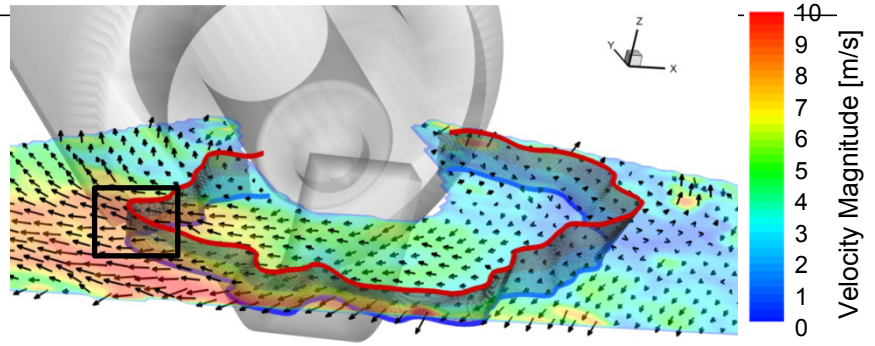
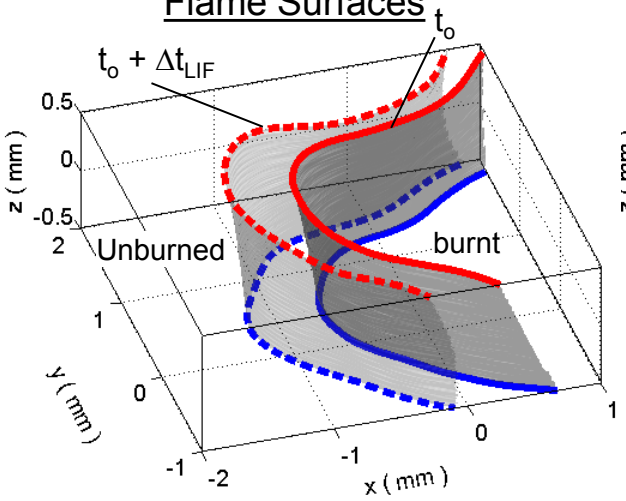
- Local flame speed
  - Absolute velocity: $\vec{U}_{Flame}$
  - Convection: $\vec{U}_{Convection}$
  - Flame speed: $\vec{n} \cdot S_T$

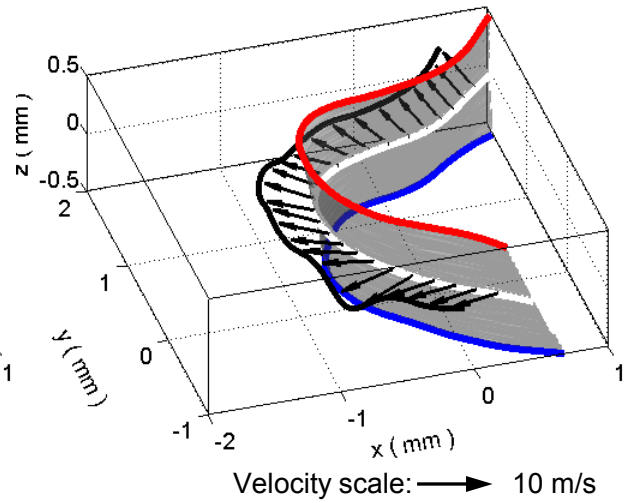




Flame Surfaces

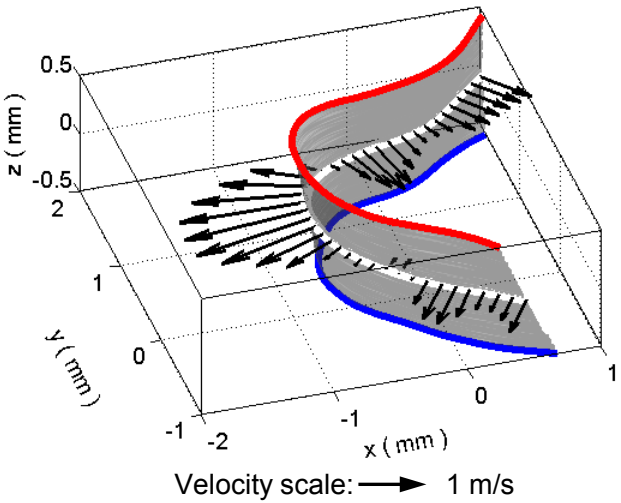


Conv. vel. 0.4 mm from surface



- Large range of convection velocities
  - 7 – 10 m/s

Flame speed in normal direction



- Turbulent flame speed
  - -1.0 – 2.5 m/s

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Turbulent flame speed during early flame dev.

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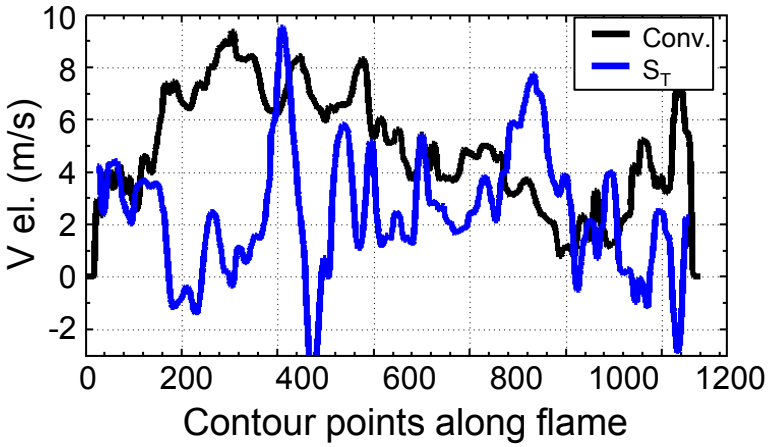
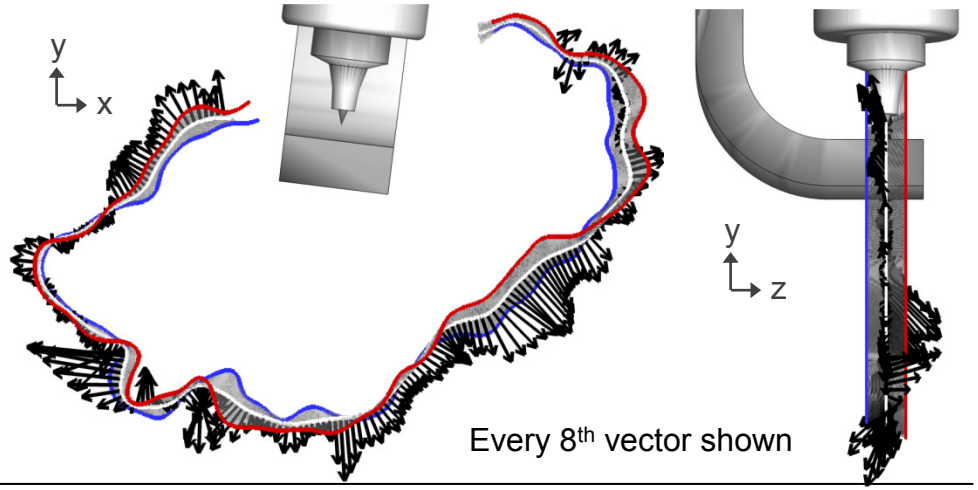
- S_T and convection along flame surface
  - Non-uniform
    - S_T: -2 – 10 m/s
    - Conv.: 0 – 10 m/s
  - 3D dependent

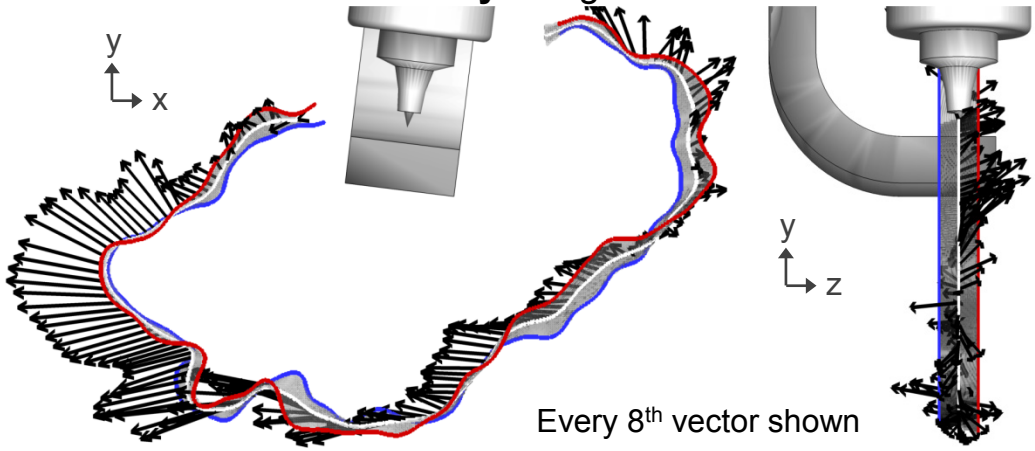
Velocity Scale: ⟶ 8 m/s



Flame speed (S_T) along flame surface



Convection Velocity along flame surface



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Flame displacement speed during early flame development

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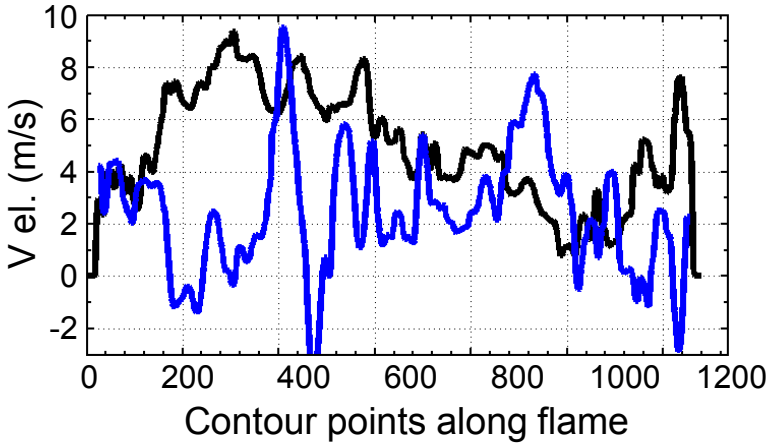
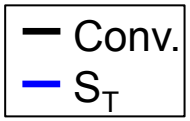
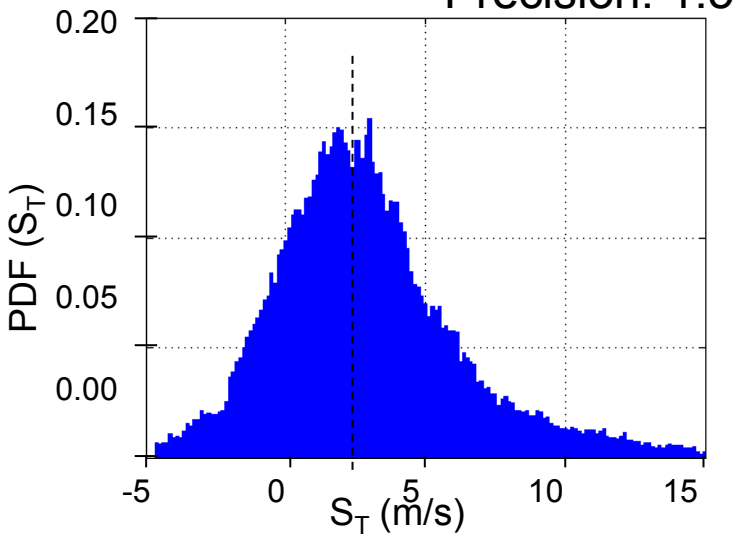
- Statistical Quantities
  - Distribution of S_T (80 cycles)





$S_T(\mu)$= 2.5 m/s
Precision: 1.5 m/s



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Statistics of turbulent flame speed

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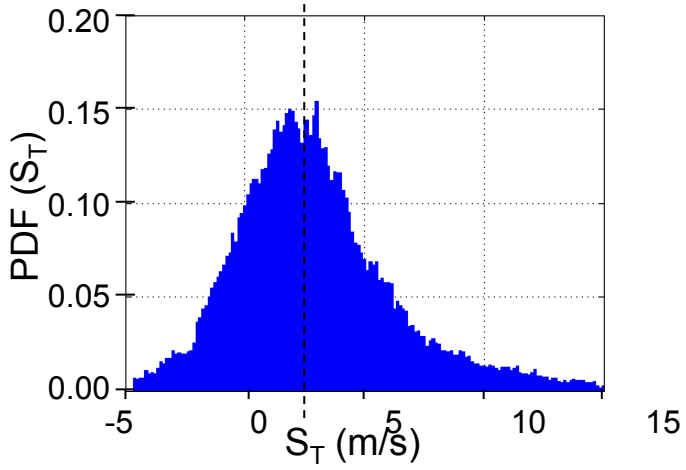
- Local flame speed: S_T: -5 – 15 m/s
- Avg. S_T = 7.2 x S_L
  - S_L = 0.36 m/s (P = 12 bar, T = 550K)
- Strong flame wrinkling due to
  - High turbulence levels
  - Thermal-diffusive /hydrodynamic instabilities (promoted by thin flames at high pressure)

$S_T(\mu)$= 2.5 m/s
Precision: 1.5 m/s



Info instabilities

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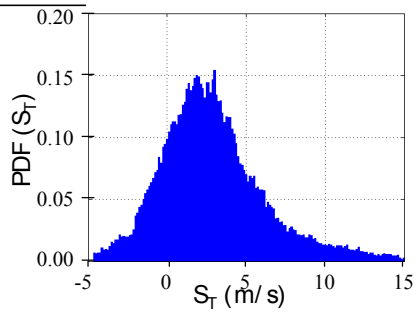
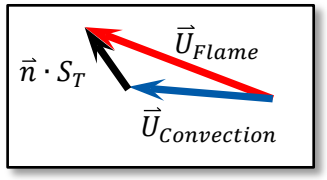
Negative end of the PDF

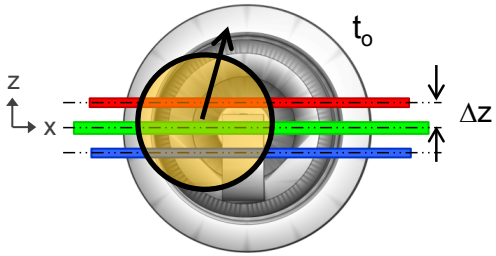
- Negative flame speeds
  - Flame displacement relative to flow
    - Not rate of consumption!





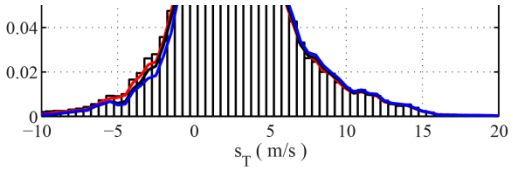
Planar imaging

- Out-of-plane transport
- Conditional analysis
  - Exclude strong *w*, convection angles



Precision

- LIF Resolution: 0.08 mm
  - ΔS_T = 1.5 m/s
  - $\Delta S_{T,MAX}$ = 3.0 m/s



Physical

- Mechanisms (DNS*)
  - High positive curvature
  - High comp. & tang. Strain
  - Sensitivity of iso-level
- No experimental correlations found
  - (Trunk 2013, Kerl 2013)
- Change of flame structure
  - Transport effects

* Gran 1996, Chen 1998, Chen 2002, Kim 2005

Tomographic OH-LIF

Work-in-Progress Poster, 36th Intl. Symp. On Combustion 2016, South Korea

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- Turbulent flow phenomena are three-dimensional in nature
- Planar OH-LIF is a common tool to investigate turbulent flame characteristics
- Information in 3rd dimension, however, is lost in planar techniques
- Turbulent flame features such as flame holes can only be characterized by fully three-dimensional measurements
- Tomographic OH-LIF imaging as an approach to yield the full three-dimensional OH concentration field

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Setup Tomo LIF

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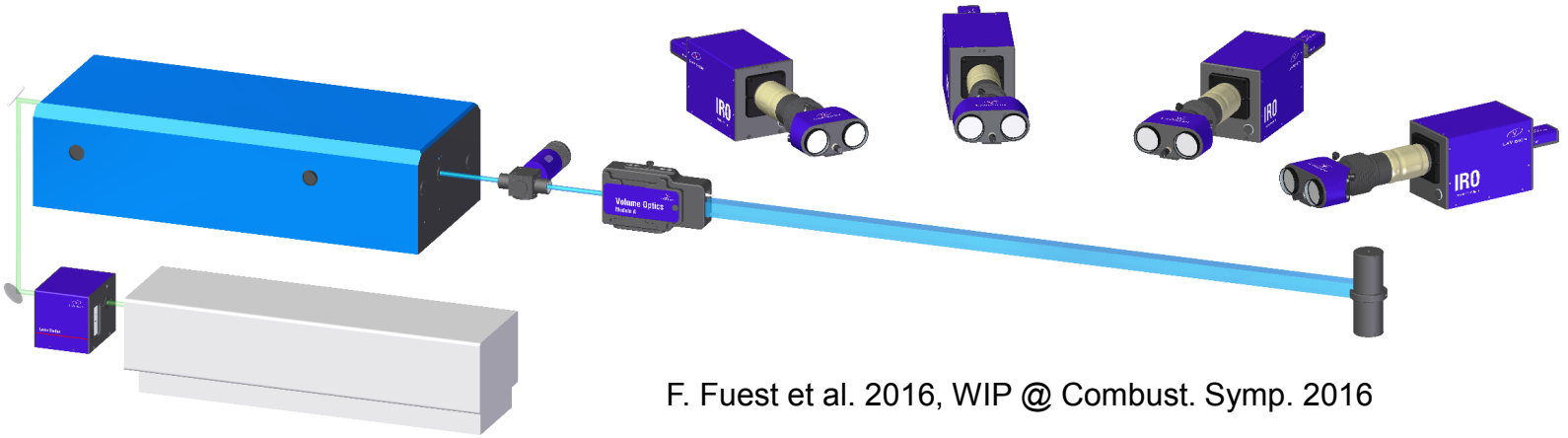
Detection

- Four intensified CCD cameras in one plane at 45° angle separation
- Image doubler
- 8 simultaneous views

Excitation

- Frequency-doubled output of a dye laser tuned to excite the $Q_1(8)$ transition (λ = 283.55 nm) of the $A^2\sum \leftarrow X^2\prod$ (v'=1, v"=0) band of hydroxyl radicals
- 20 mJ at probe volume of **3x3x3 cm^3**



F. Fuest et al. 2016, WIP @ Combust. Symp. 2016

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Tomographic reconstruction
Example turbulent Bunsen flame

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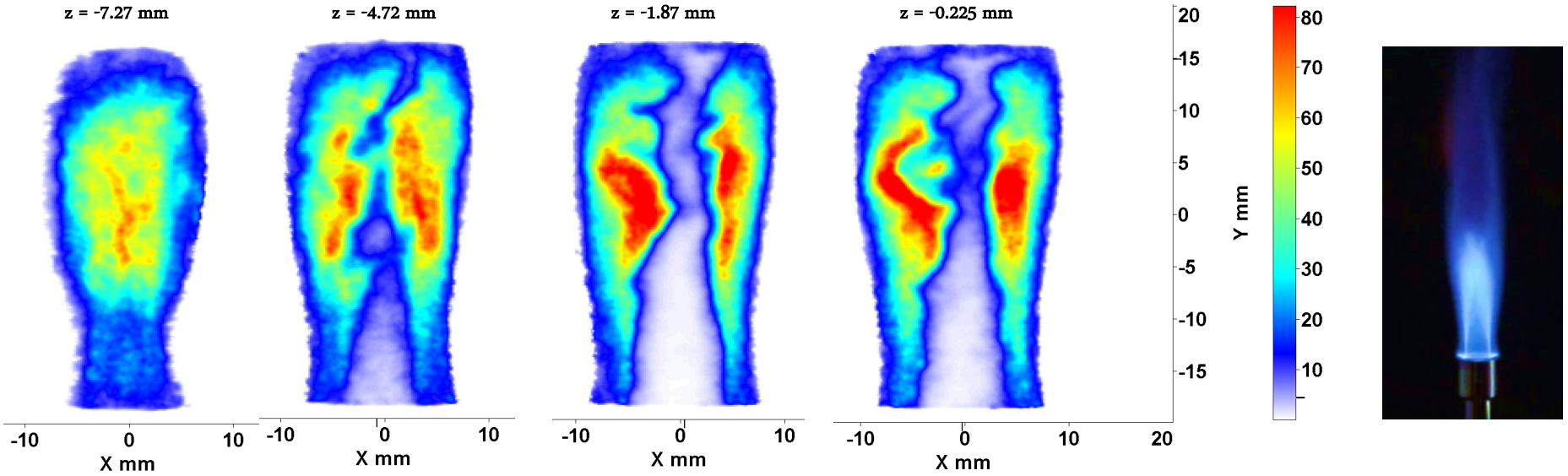
- Simultaneous Multiplicative Algebraic Reconstruction Technique (SMART)
- 100 iterations
- Computational time for 8 views @ 16 cores (3.10 GHz, 128 GB RAM):
  - 5 min for 100M voxel of 75^3 µm^3, no binning,
  - 45 s for 12M voxel of 150^3 µm^3, 2x2 binning

Reconstructed z-planes of turbulent Bunsen flame



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Tomographic reconstruction
Example turbulent Bunsen flame

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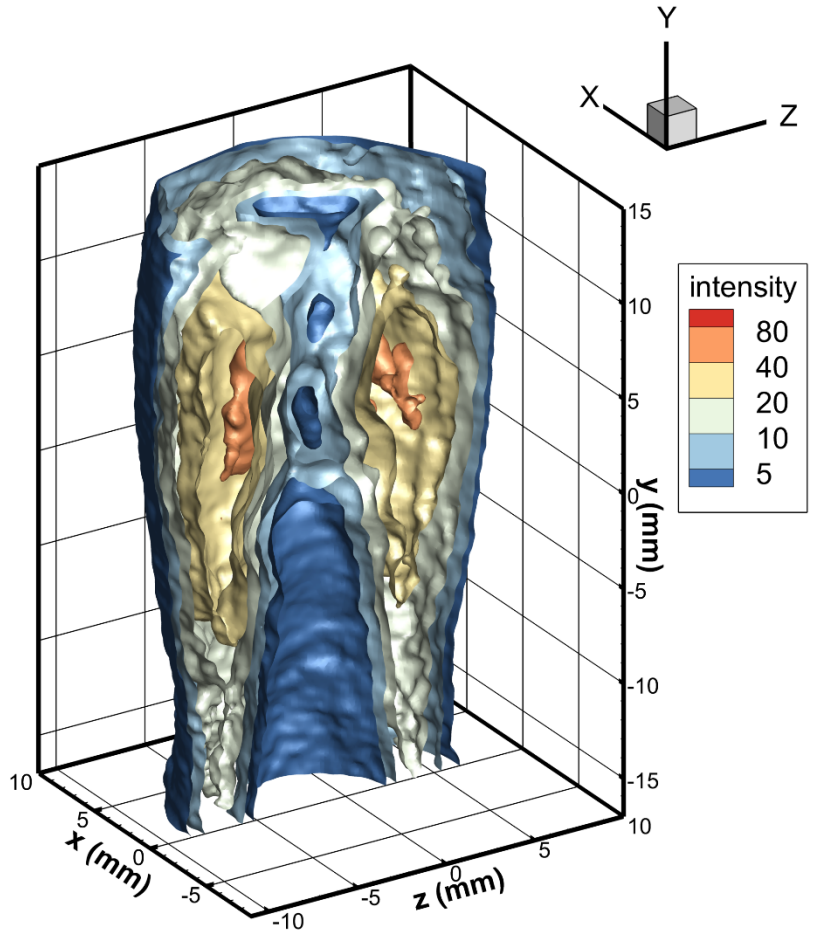
➢ **Reconstructed 3D iso surface of LIF intensity**



F. Fuest et al. 2016, WIP @ Combust. Symp. 2016

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Comparison with 2D PLIF measurements
Laminar Bunsen flame

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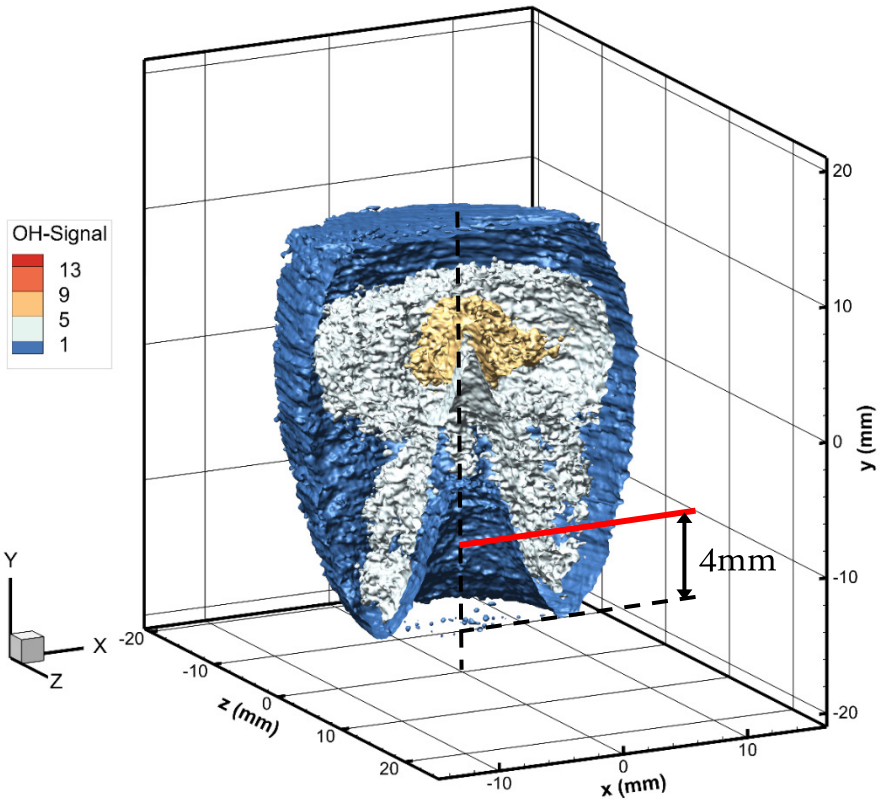
- Tomographic LIF and PLIF at same location
- Laminar premixed methane flame, d = 13 mm
- Center plane
- One side of OH-LIF profile
- 4 mm above the nozzle exit

Reconstructed single-shot laminar flame and location of extracted intensity profiles.



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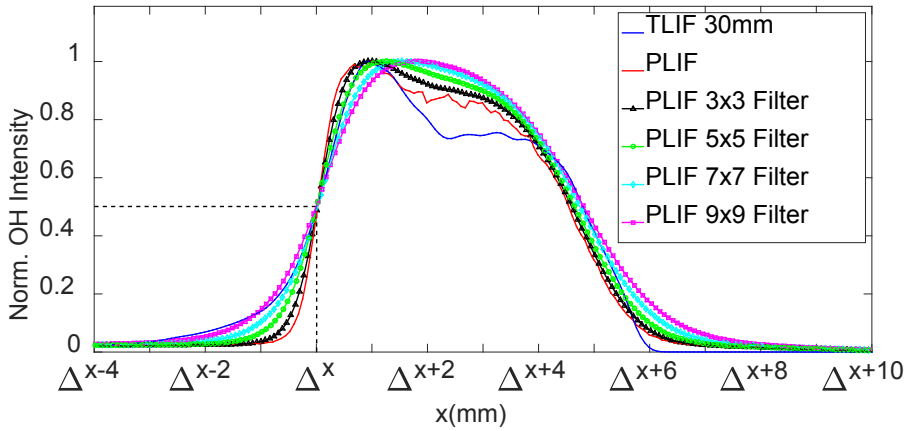
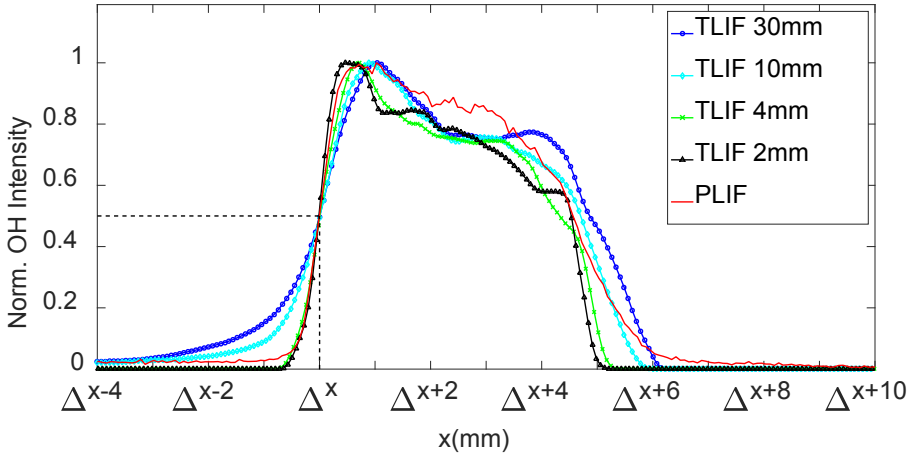
Comparison with 2D PLIF measurements

- Different filter sizes for PLIF and different volume-sheet thicknesses for tomographic LIF

→PLIF using 5x5 filter shows similar gradient at large OH intensity

→Steeper gradient with decrease of sheet thickness

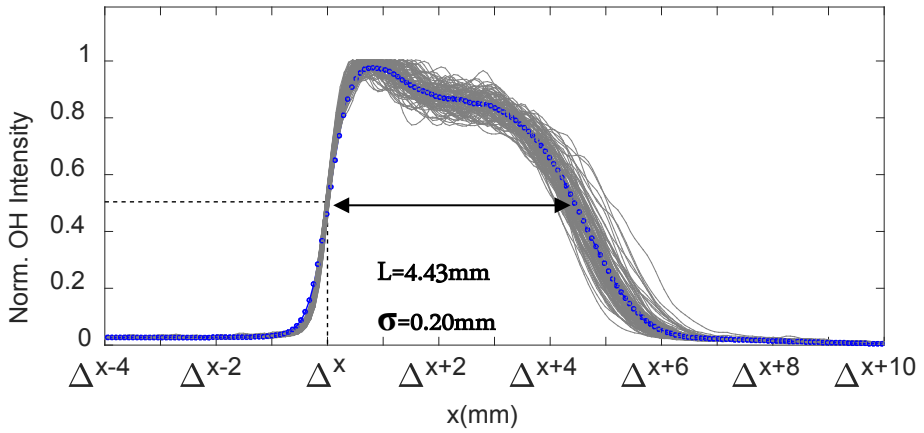




F. Fuest et al. 2016, WIP @ Combust. Symp. 2016

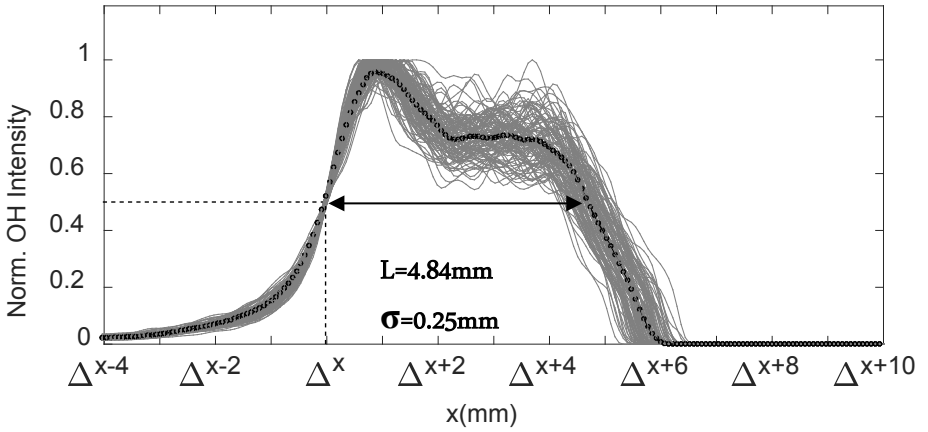
Comparison with 2D PLIF measurements

- **PLIF**: Single-shot and average profile



- **TLIF**: Single-shot and average profile

  Length L at 50% intensity and its standard deviation σ



Turbulent lifted flame

Re 5000, voxel of 75^3 µm^3, no binning

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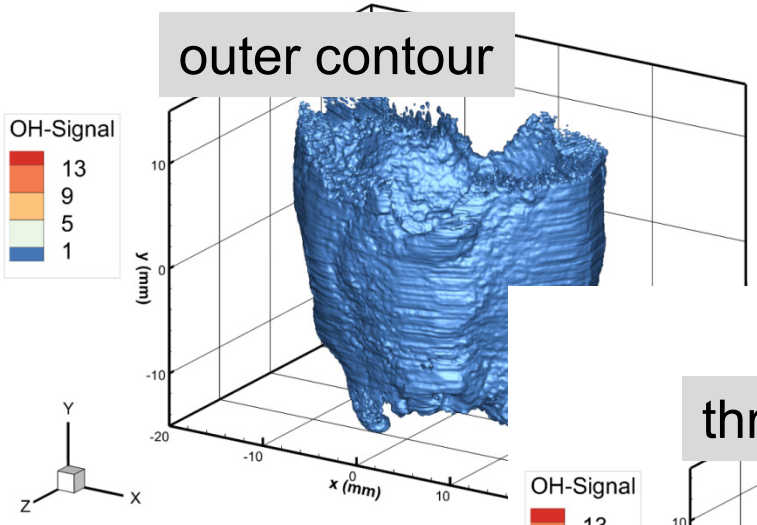
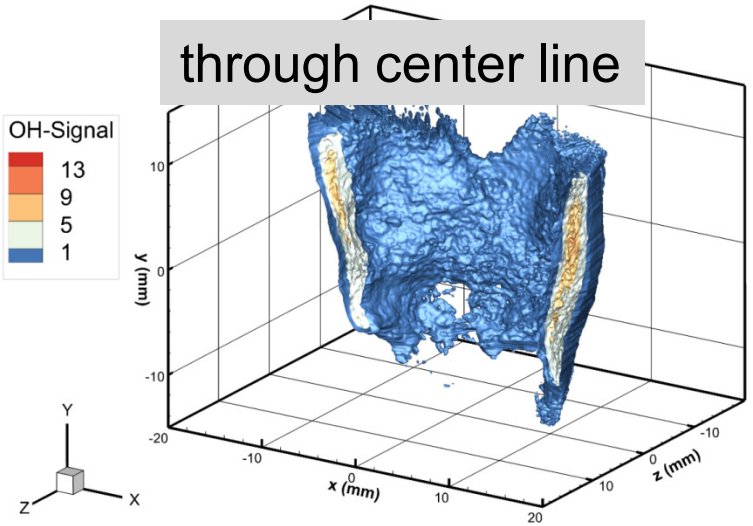
outer contour



through center line



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Turbulent lifted flame

Re 5000, voxel of 75^3 µm^3, no binning

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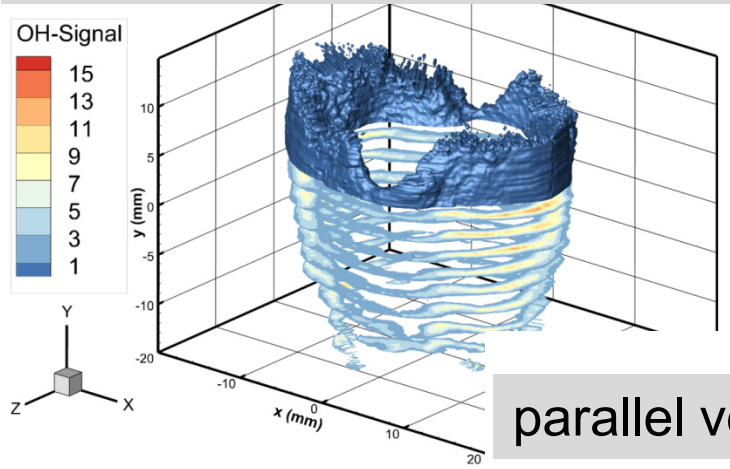
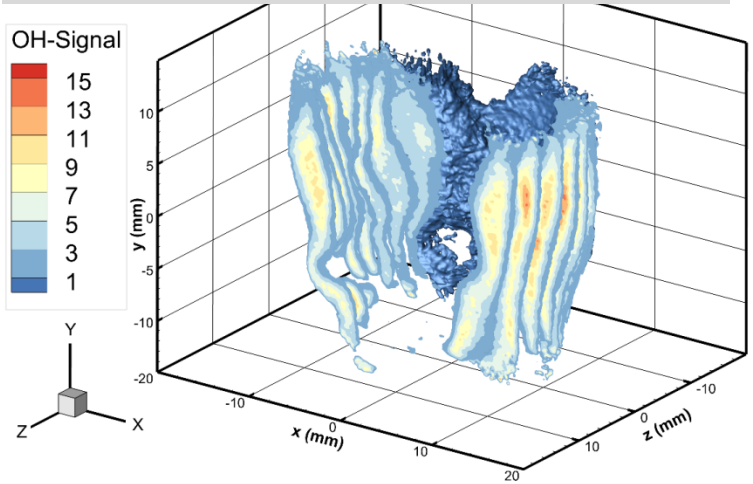
parallel horizontral cross section



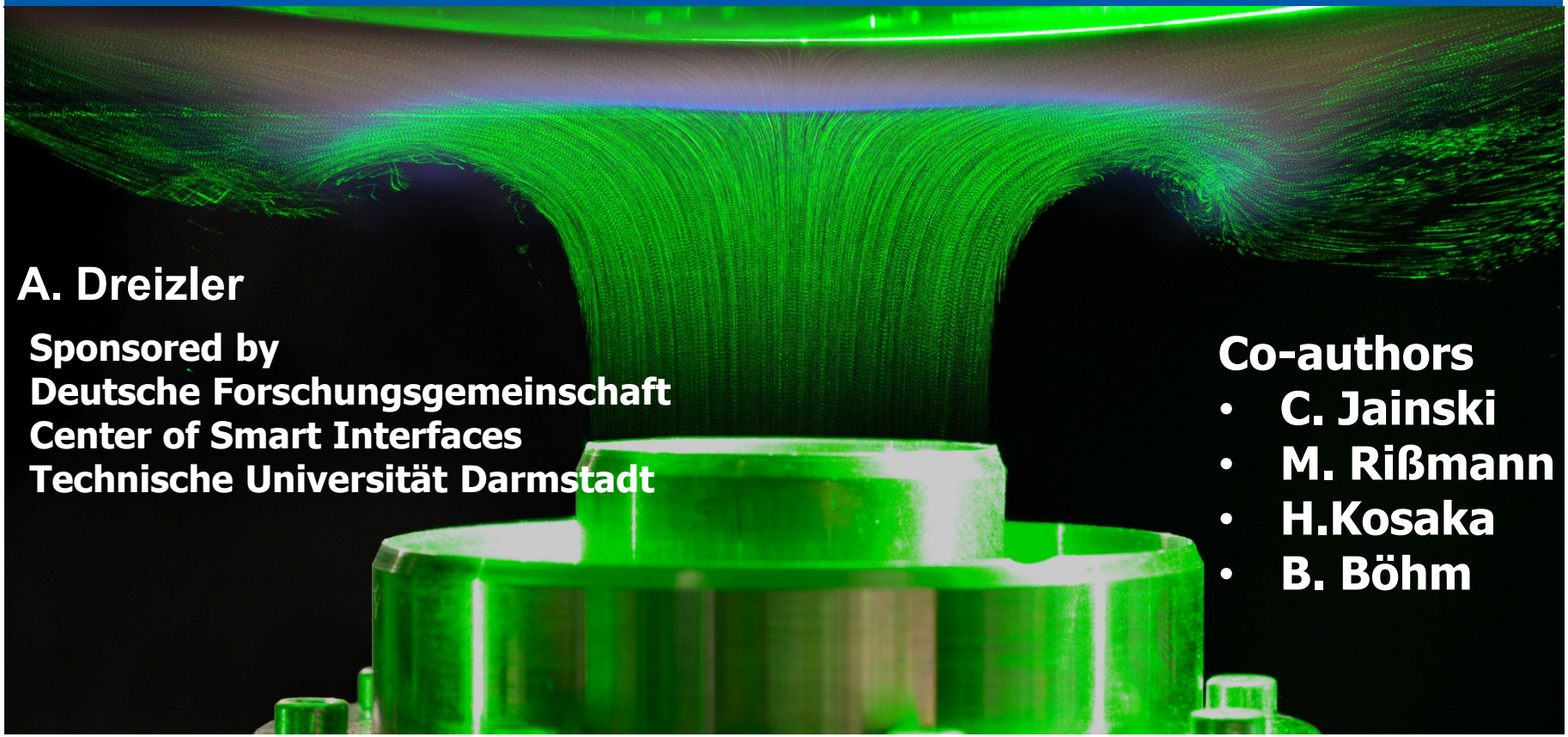
parallel vertical cross section



RSM Reaktive Strömungen + Messtechnik

Chapter 9: Flame wall interactions in canonical configurations

TU Darmstadt, Germany
Dept. of Mechanical Engineering
Institute for Reactive Flows and Diagnostics



A. Dreizler

Sponsored by
Deutsche Forschungsgemeinschaft
Center of Smart Interfaces
Technische Universität Darmstadt

Co-authors
- **C. Jainski**
- **M. Rißmann**
- **H.Kosaka**
- **B. Böhm**

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- Motivation of Flame-Wall Interaction (FWI) Research
- Experimental Approach at RSM/TU Darmstadt
- Head-on Quenching
  - Flame dynamics of turbulent flames
  - Thermo-chemical states
- Side Wall Quenching
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    - Flame surface density
    - Mean reaction rate modelling
  - Thermo-chemical states
    - Laminar flames
    - Turbulent flames

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Flame-wall interaction (FWI)

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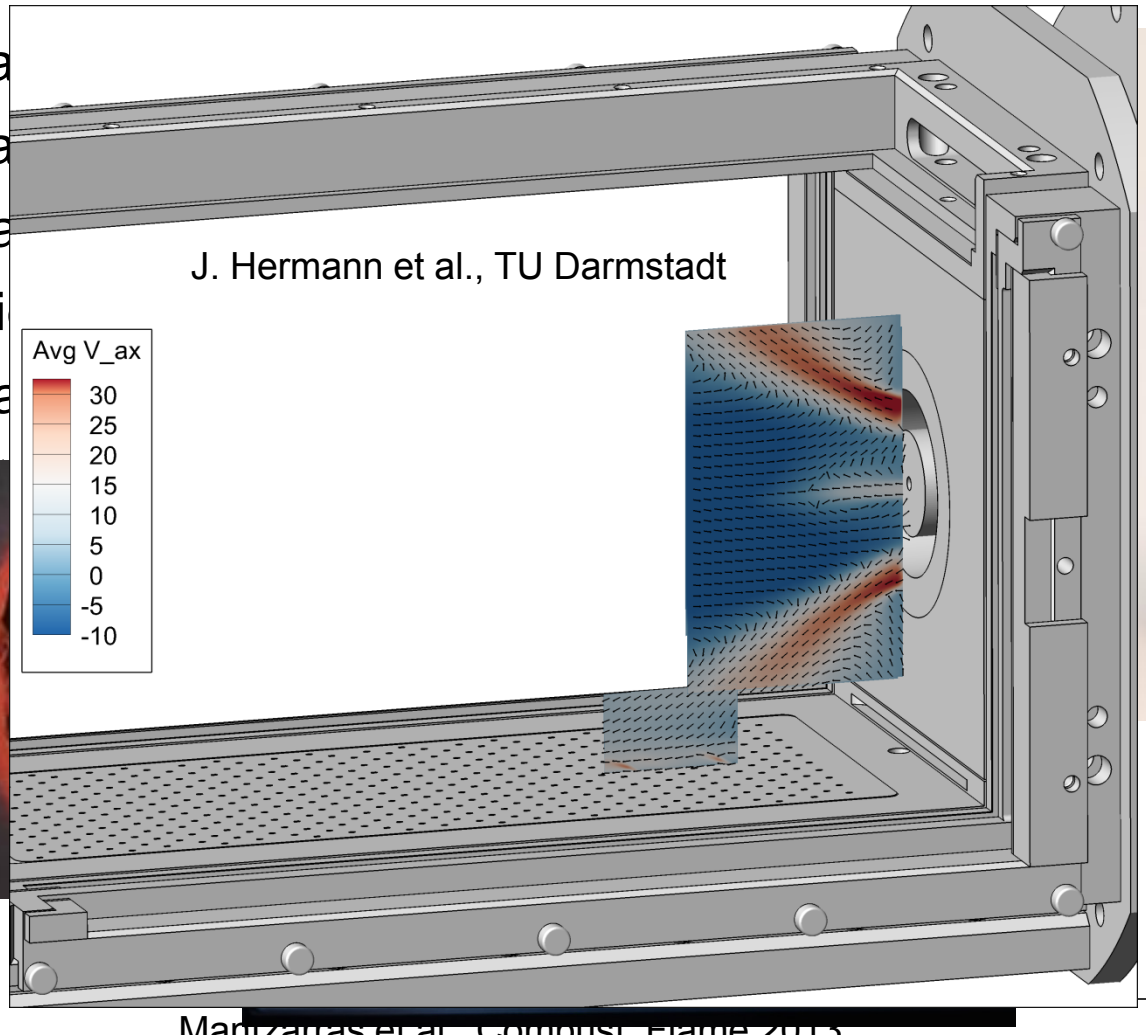
- Topica
  - Sa
  - Ca
  - Mi
  - Ga
  -



Mantzaras et al., Combust. Flame 2013

Davy's mine lamp
British Museum (1817)

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General properties of FWI

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- When flame approaches closer than a few flame thicknesses to the wall (for premixed combustion)

→ Intense coupling between flame and wall

  - Large heat fluxes (exceeding 1 MW/m^2 for HC-fuels at 1 bar)
  - Flame quenching causing incomplete combustion
    - Emission of unburned hydrocarbons and CO
    - Relevant especially for cold-start **engine conditions**

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Flame-Wall Interaction in IC engines

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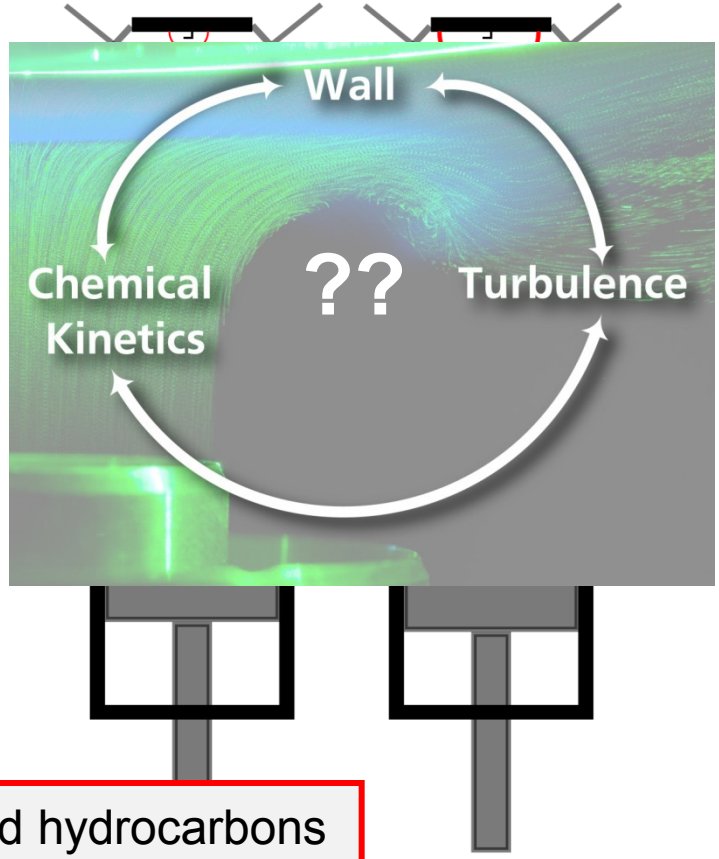
- Turbulent flame (**1500-2500 K**) surrounded by cold walls (**≤700 K**)
- **Heat losses** and **radical recombination** leads to flame quenching
- Incomplete combustion generates **UHC, CO** and **soot**
- Flame – wall interactions affect **efficiency** and **pollutant formation** [Alkidas, PECS 1999]



30% combustion energy in an engine is lost by heat transfer trough the wall

40% of unburned hydrocarbons in engines is due to flame – wall interactions

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Flame-Wall Interaction in IC engines: Temperature rise due to flame impact at piston

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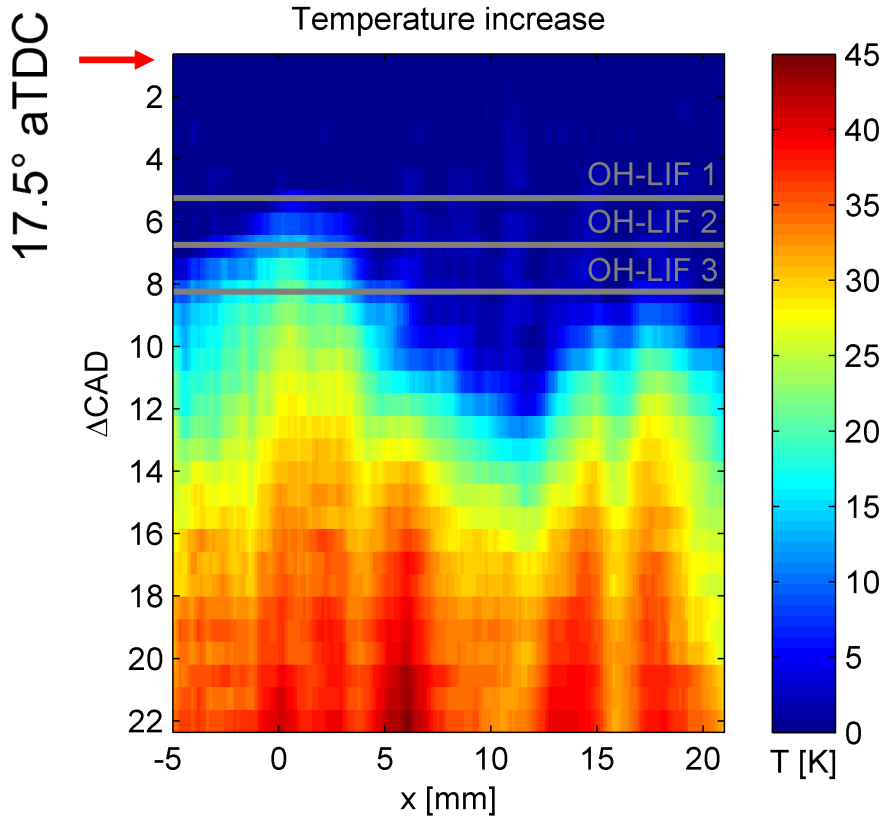
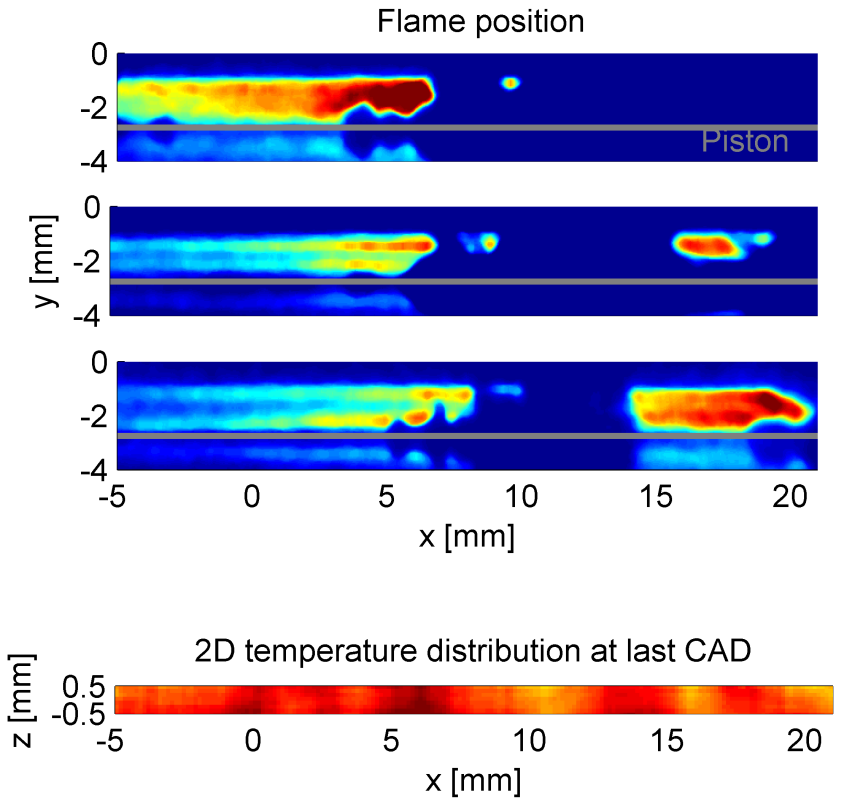


Time-resolved phosphor thermometry
(ZnO:Zn)



Time-resolved flame tracking by OH-PLIF

C.-P. Ding et al., Appl. Phys. B 2017

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Flame-Wall Interaction in IC engines

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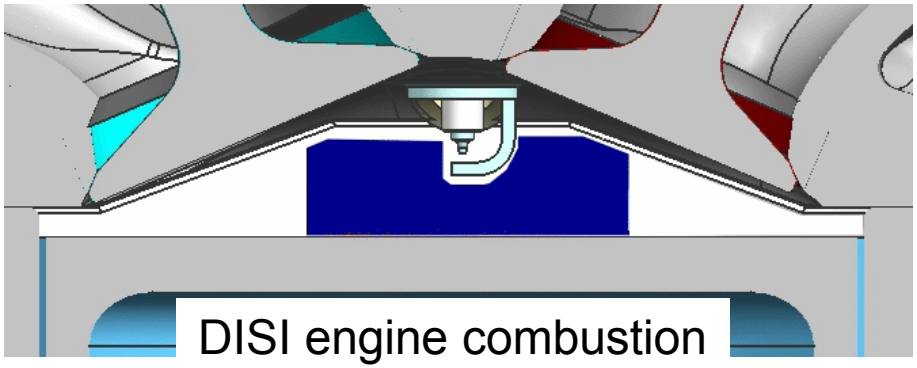
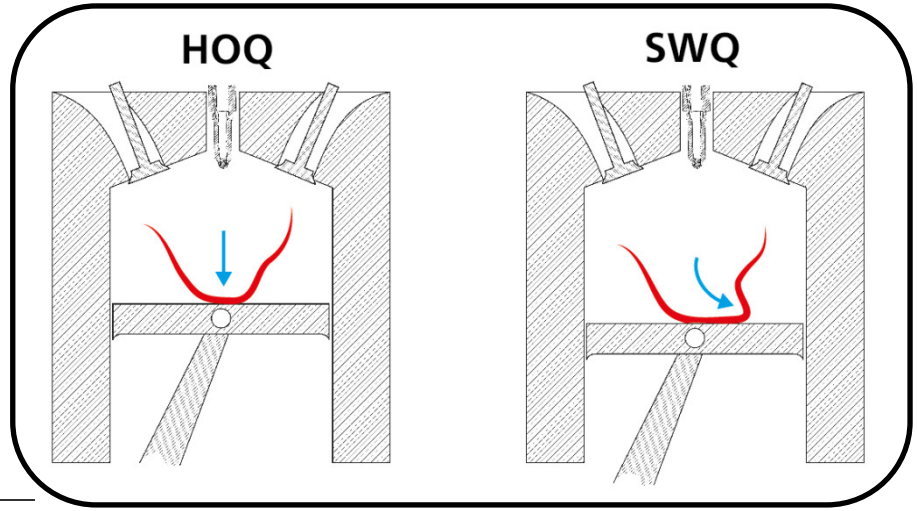
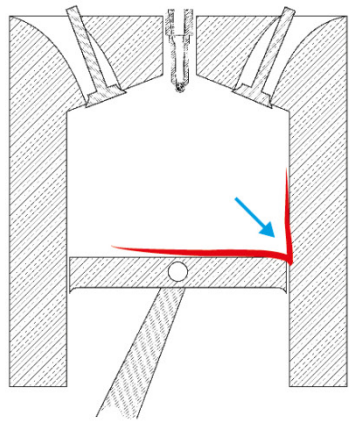
- Focus here: **premixed** flames



Cinematographic Mie scattering of evaporating droplets

Classification
Canonical geometries





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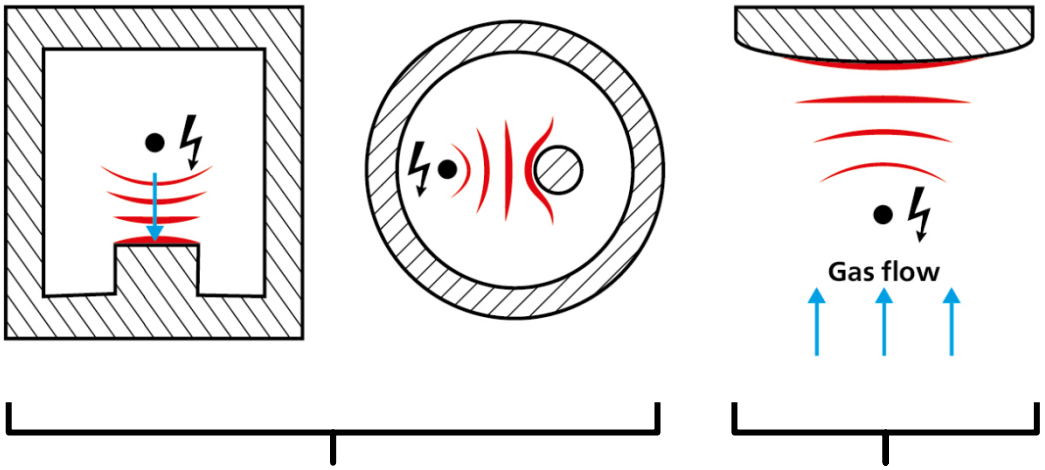
Head-on quenching – canonical geometries

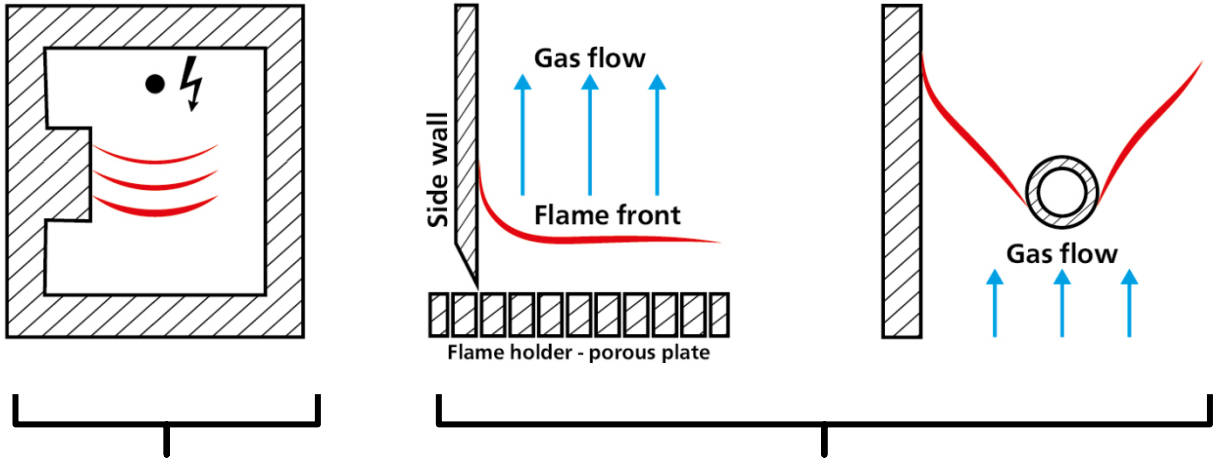


Renou group
Mounaim-Rouselle group
Bellenoue group

Saggau

Dreizler group

Sidewall quenching – canonical geometries



Bellenoue group.

Clendening group
Saffmann
Schulz, Dreier group

Escudie group
Dreizler group

Dynamics of HOQ: 1D-simulation

Source: T. Meier, G. Künne; A. Keteheun, J. Janicka (Darmstadt)

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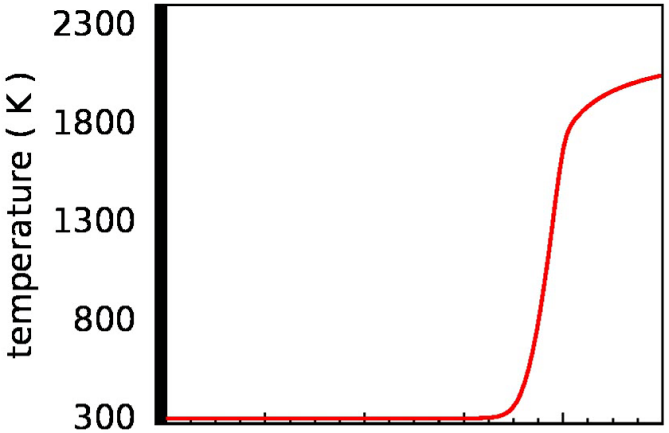
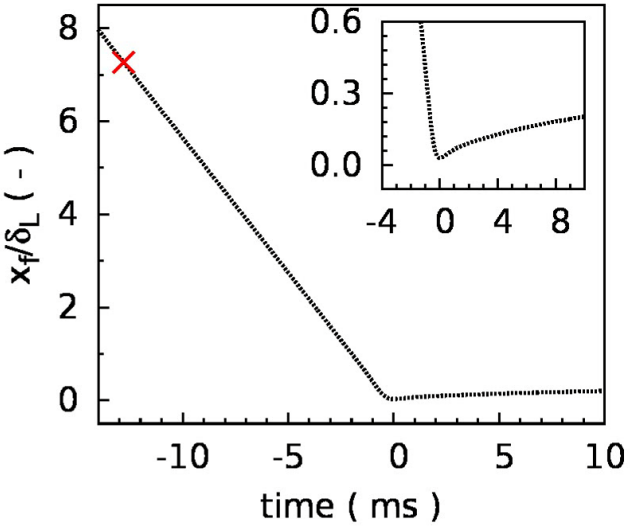
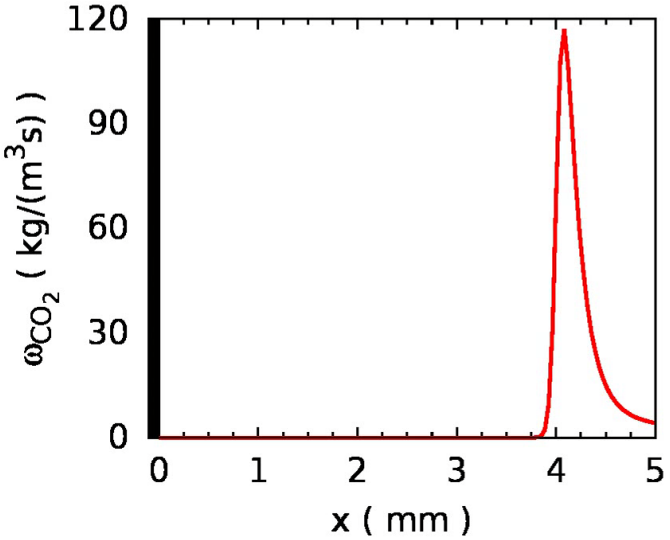
Spatial temp. profile

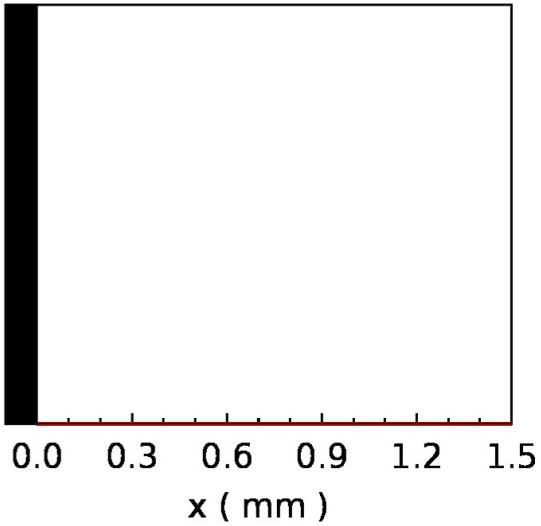




Norm. wall distance as fct. of time

CO_2-source term





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Results of 1D-DNS

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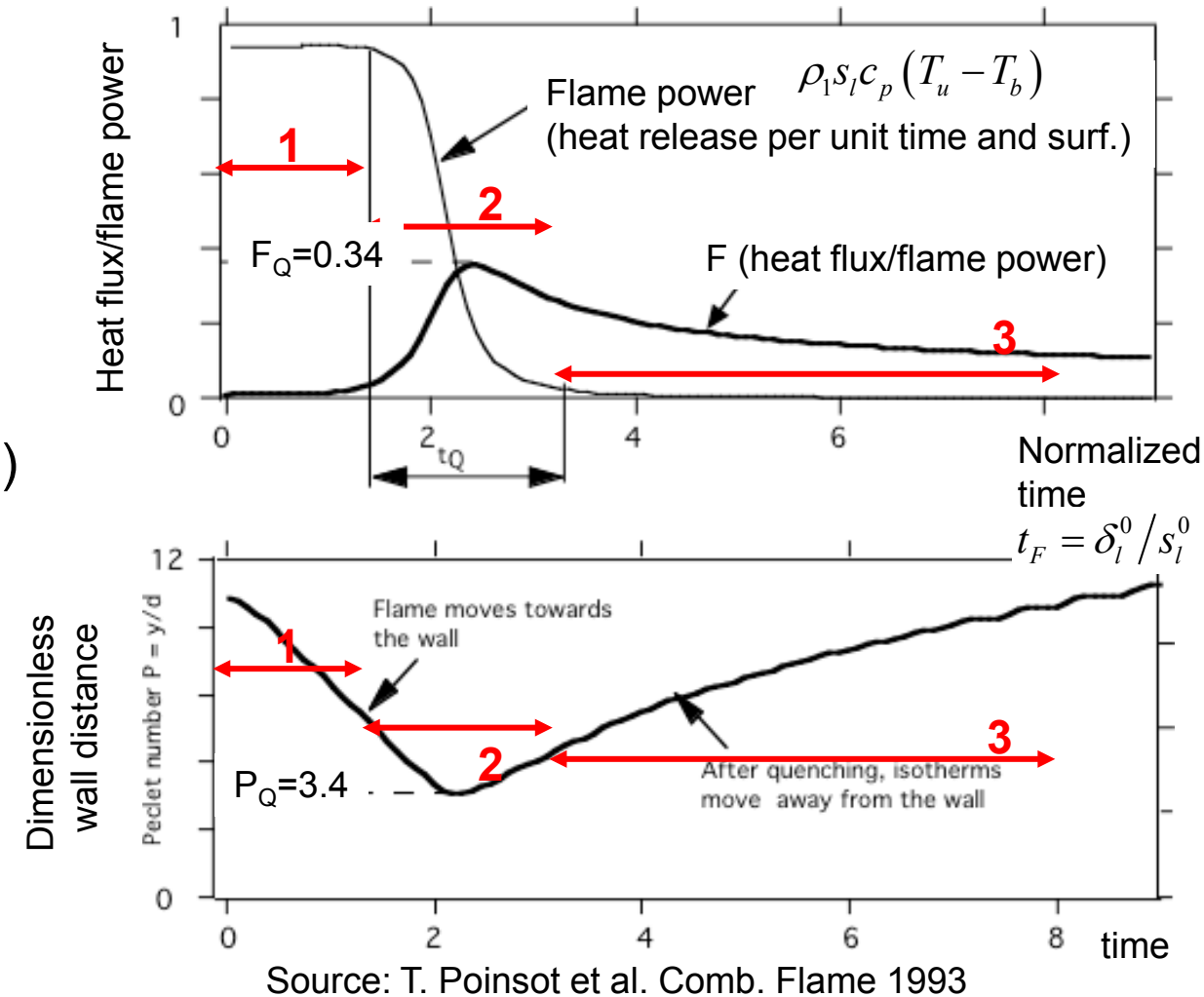
Three stages

- Flame approach (1)
- Flame quenching (2)
- Post-quench period (3)

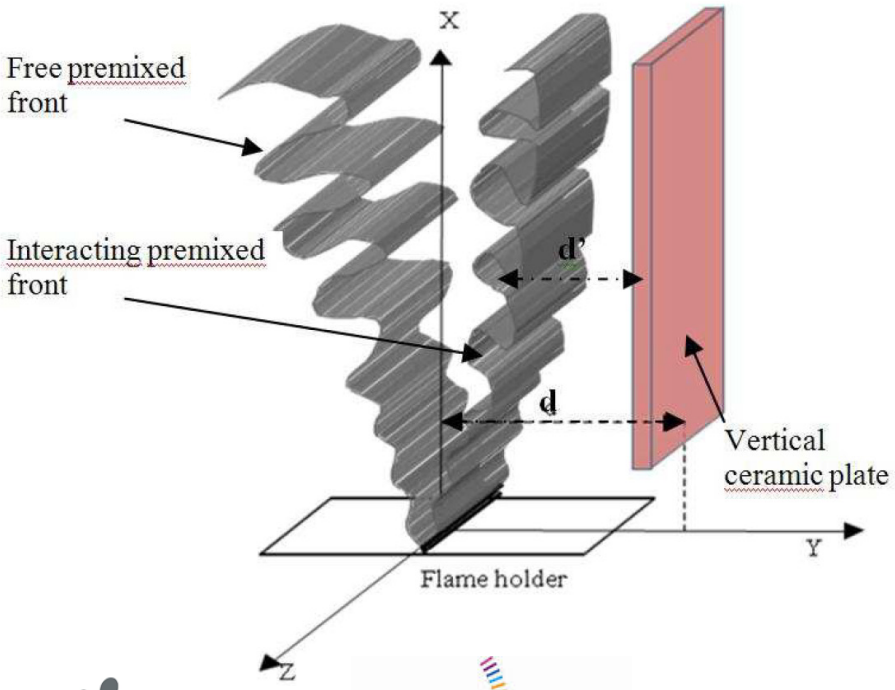


Source: T. Poinsot et al. Comb. Flame 1993

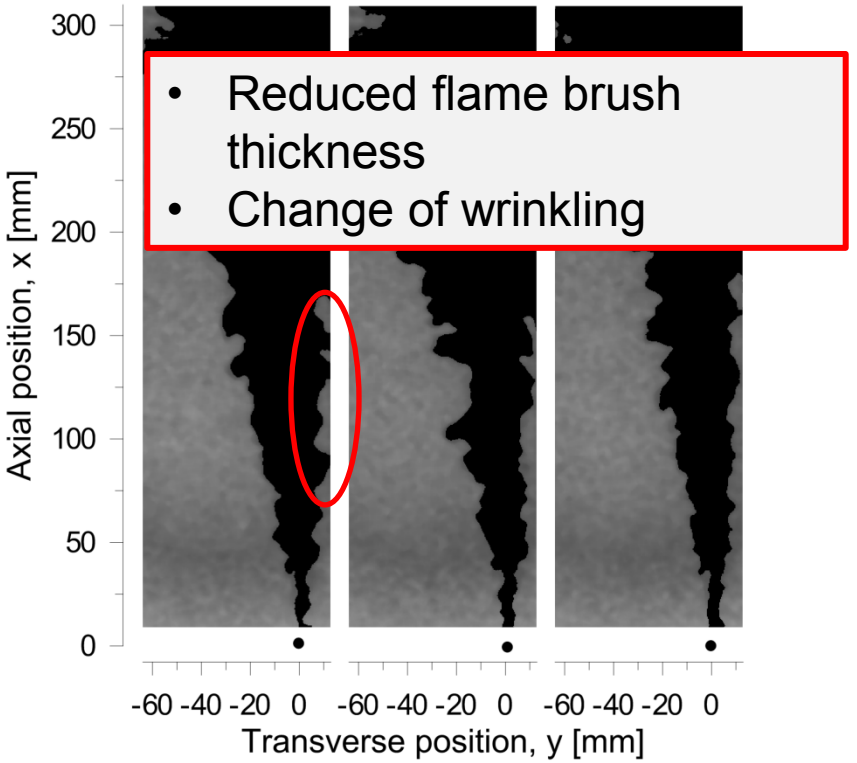
Impact of turbulence

- Vena et al. (Escudie group)

  V-flame, stabilized by rod

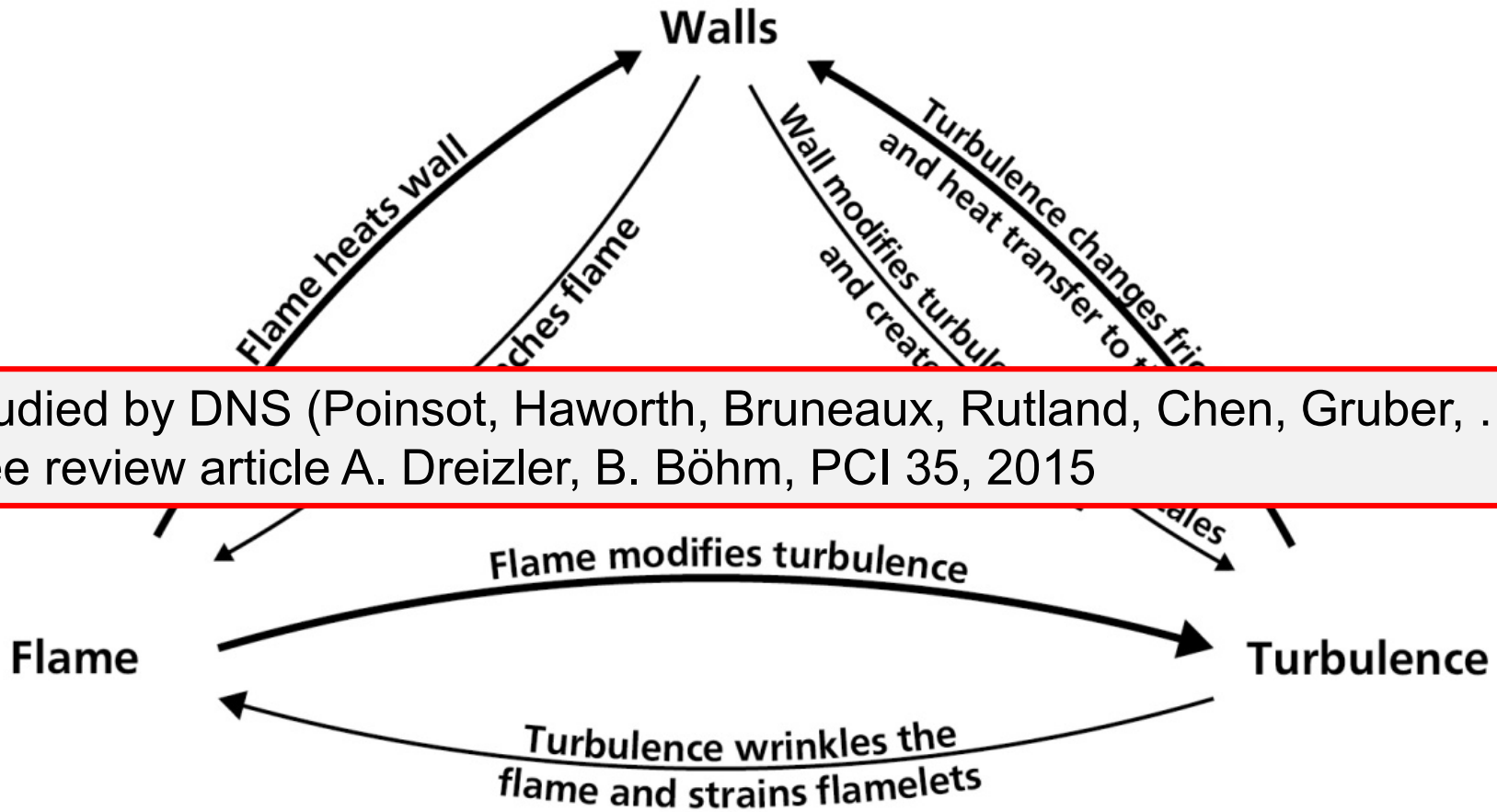


Flame visualization by Mie scattering
3 snap shots



Source: P. Vena et al. (2012), Intl. Symp. Transport Phenomena

Impact of turbulence in FWI



Studied by DNS (Poinsot, Haworth, Bruneaux, Rutland, Chen, Gruber, …)
See review article A. Dreizler, B. Böhm, PCI 35, 2015

Source: T. Poinsot and D. Veynante, Theoretical and Numerical Combustion 2005

Conclusions from previous studies

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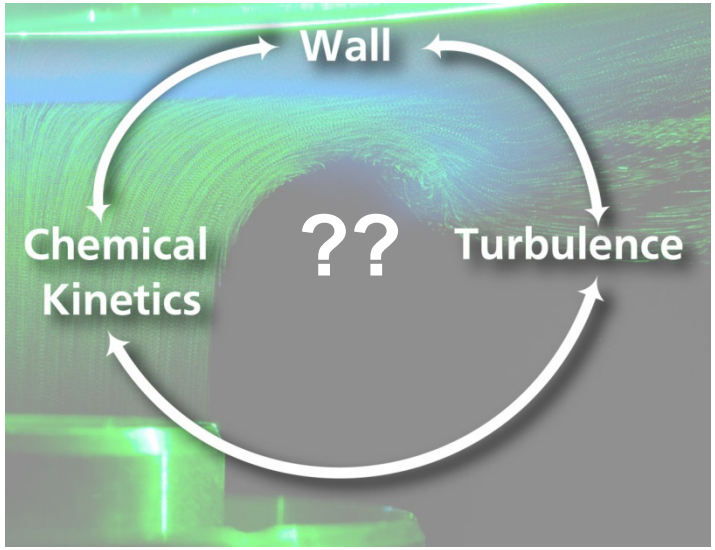
- Lack of detailed **experimental** studies providing **quantitative data**
- The focus was primarily on quenching distances and heat transfer
- Analysis of **boundary layers**, **flame structure** and **thermo-chemical states** during flame-wall interaction is limited



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Fundamental Flame-Wall Interaction

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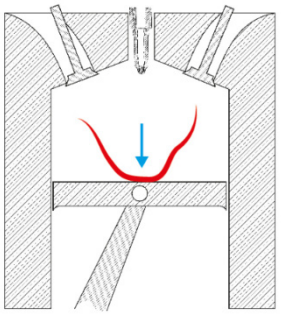
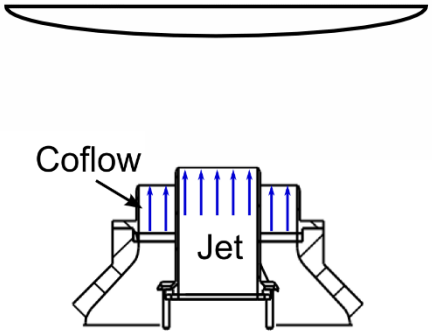
Head-on quenching

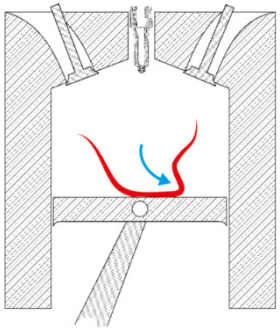


HOQ Burner

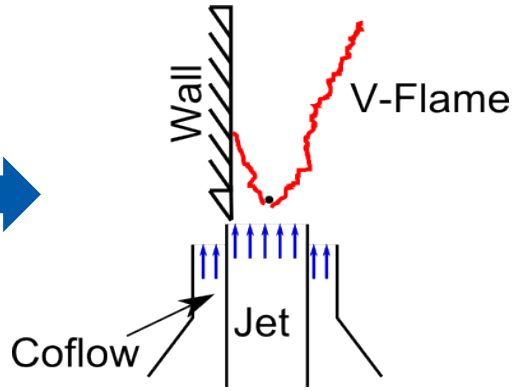


- transient
- 1D when laminar
- flame ignited by laser spark
- low sample number

Side-wall Quenching



SWQ Burner



- Statistically stationary
- 3D
- high sample number

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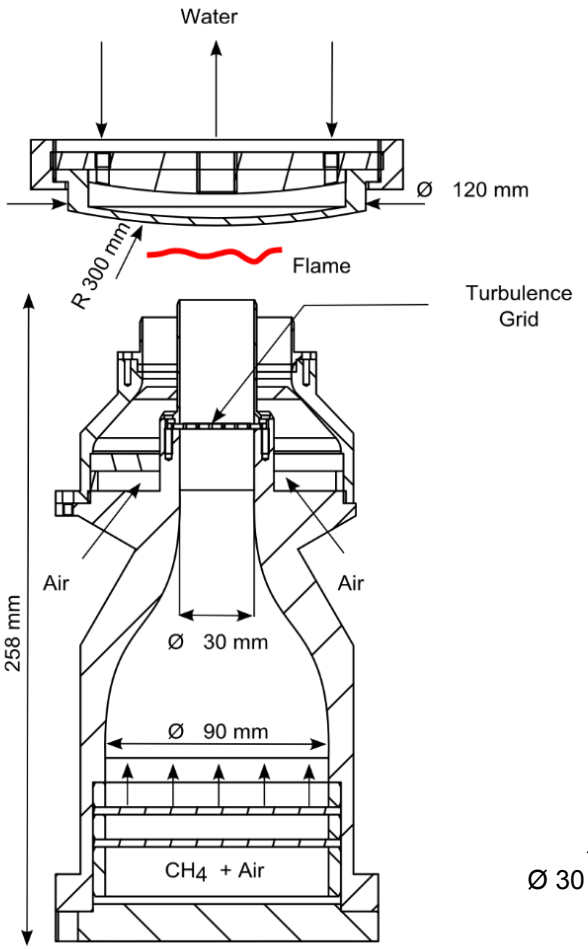
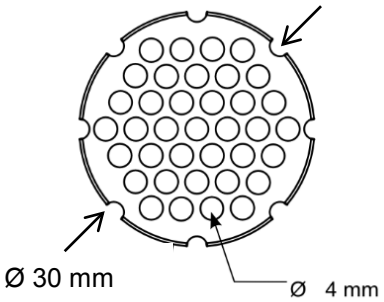
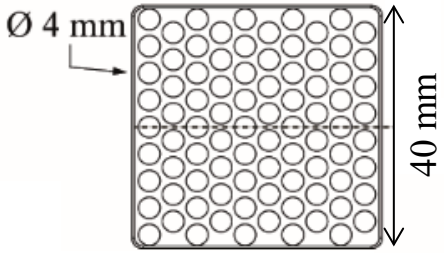
Experimental conditions

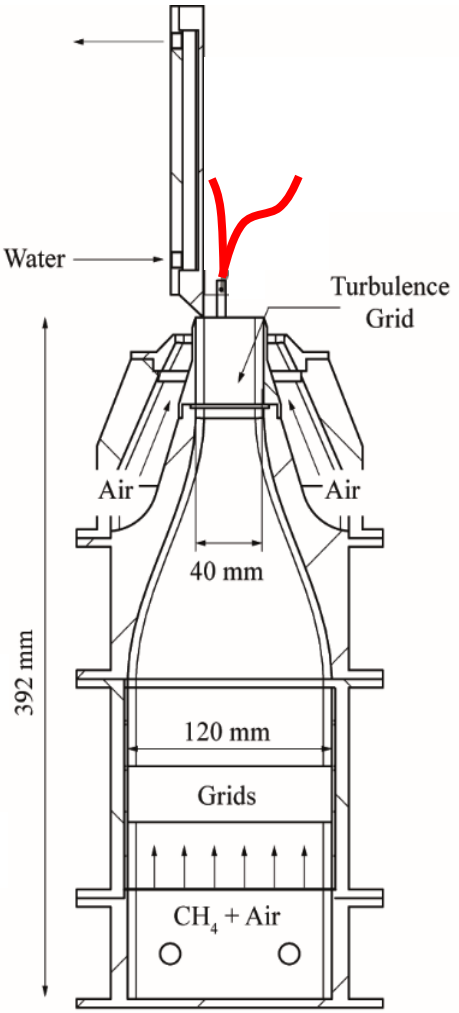


HOQ SWQ

- premixed CH_4 + air
- Φ = 0.83, 1, 1.2
- Re = 5000
- laminar and turbulent (by turb. grid)
- water cooled wall



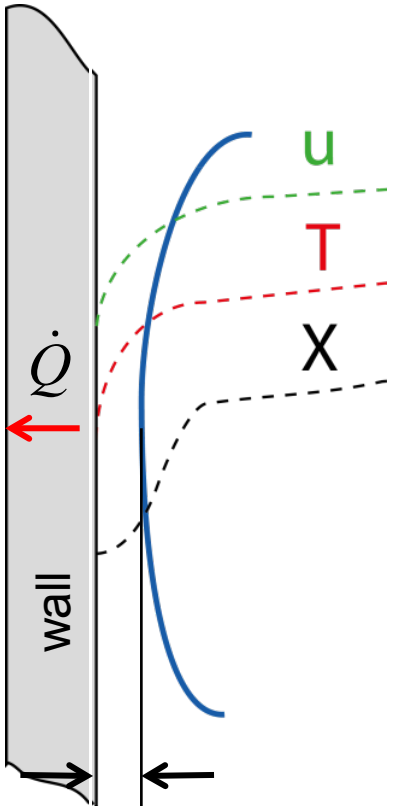




Experiments in FWI: parameters of interest

- Quenching distances, visualization of flames near walls
- Wall temperature and heat flux $\dot{Q}$
- Flow field studies near walls
  - Velocity boundary layers **u**
- Reaction rates near walls
- Thermo-chemical states during FWI
  - Thermal boundary layers **T**
  - Concentration boundary layers **X**

Focus today



Quenching distance

Measurement techniques

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Laser based diagnostics

- Non intrusive
- High spatial and temporal resolution
- High accuracy and precision
- Simultaneous measurement of several quantities – multi-parameter diagnostics

Gas Velocity	Flame Front Position	Gas Temperature	CO Concentration
(Stereo) Particle Image Velocimetry (**PIV**)	Planar **LIF** of **OH** radical Flame front from OH gradient	ro-vibrational ns-**CARS**	Two Photon **LIF** of **CO** molecule
2 D/3 Components Rep. Rate: 10 kHz	2 D Rep. Rate: 10 kHz/10 Hz	0 D Rep. Rate: 10 Hz	0 D Rep. Rate: 10 Hz

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Particle Image Velocimetry – PIV

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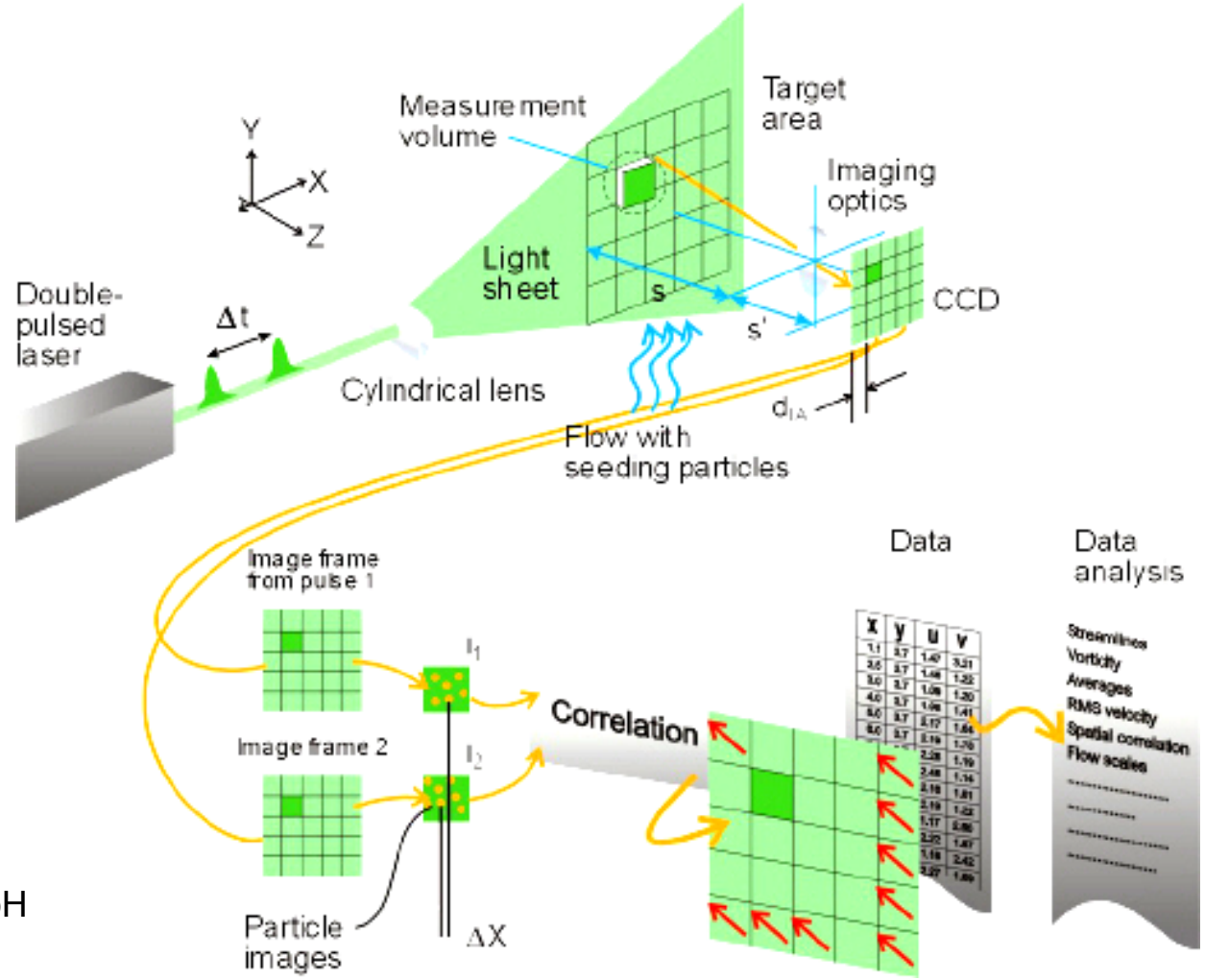
Principle 2D/2C-PIV



Source: La Vision GmbH

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Particle Image Velocimetry – PIV

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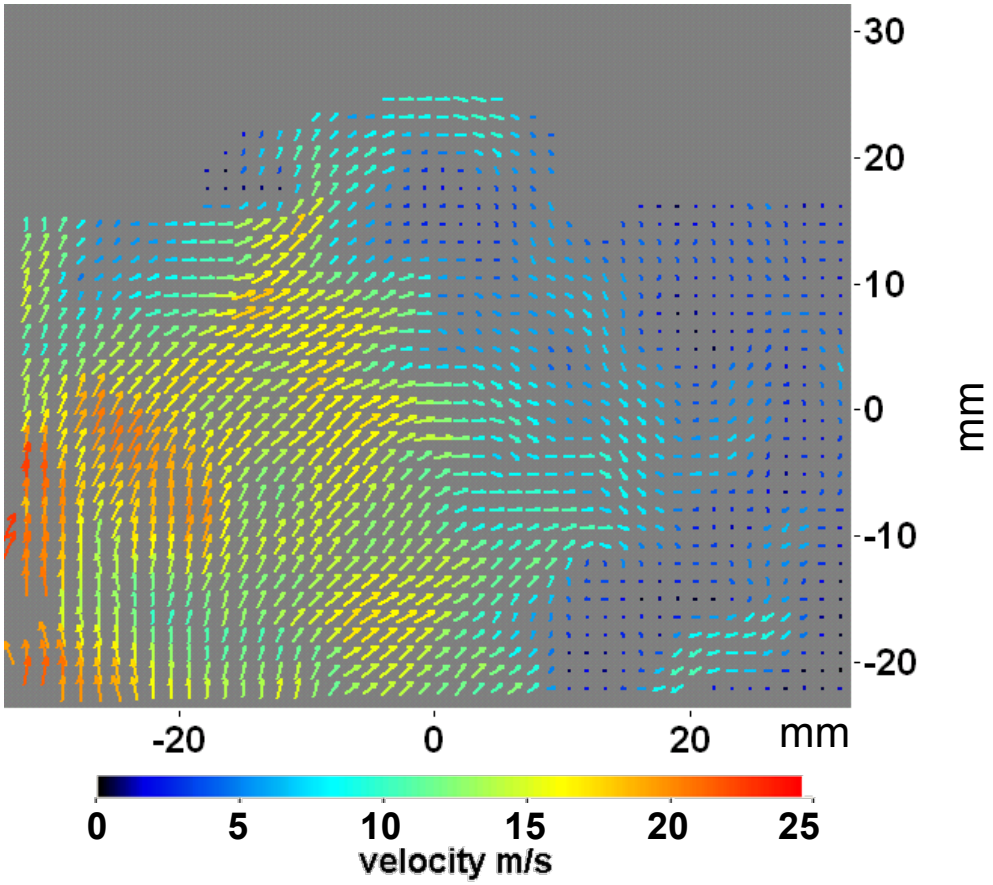
Visualization

In-cylinder meas.



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Laser Induced Fluorescence – LIF

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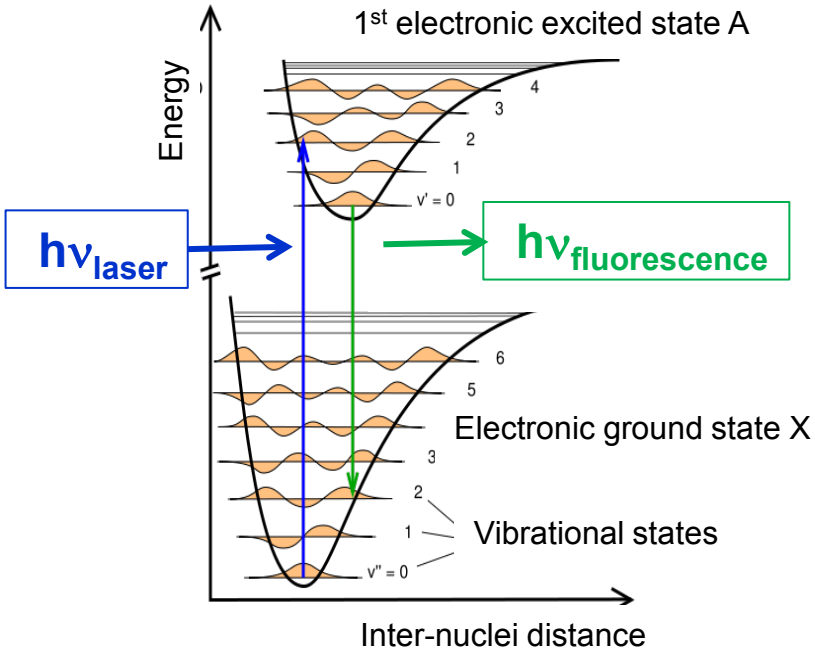
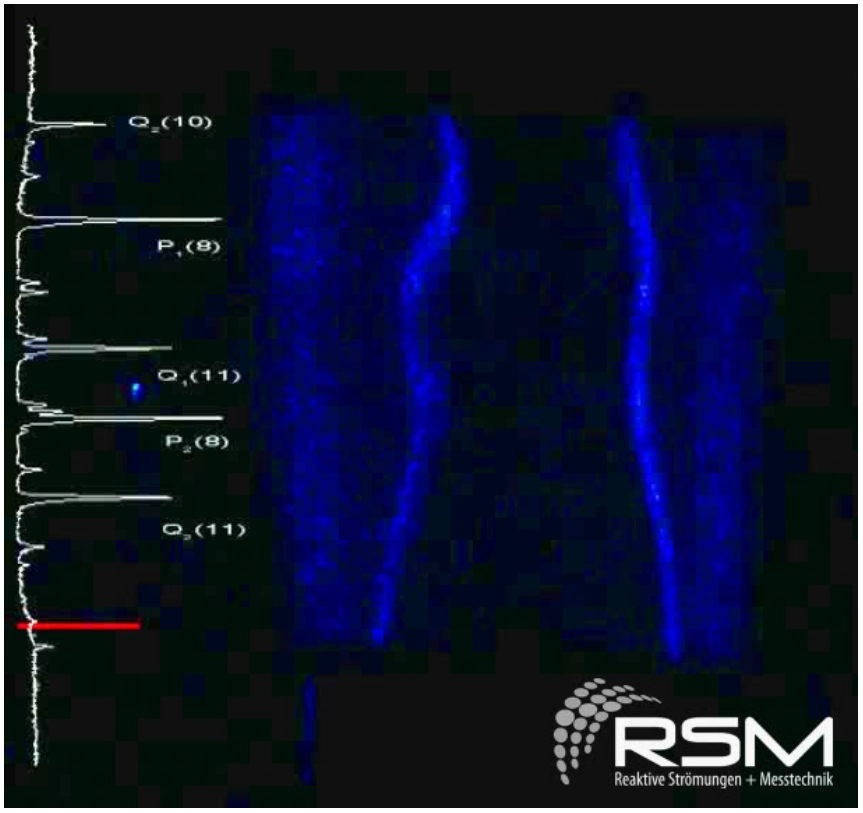
Schematic of LIF (single-photon)



Rotational sub-states not shown

OH planar LIF in fuel rich Bunsen flame
→ Flame front tracking



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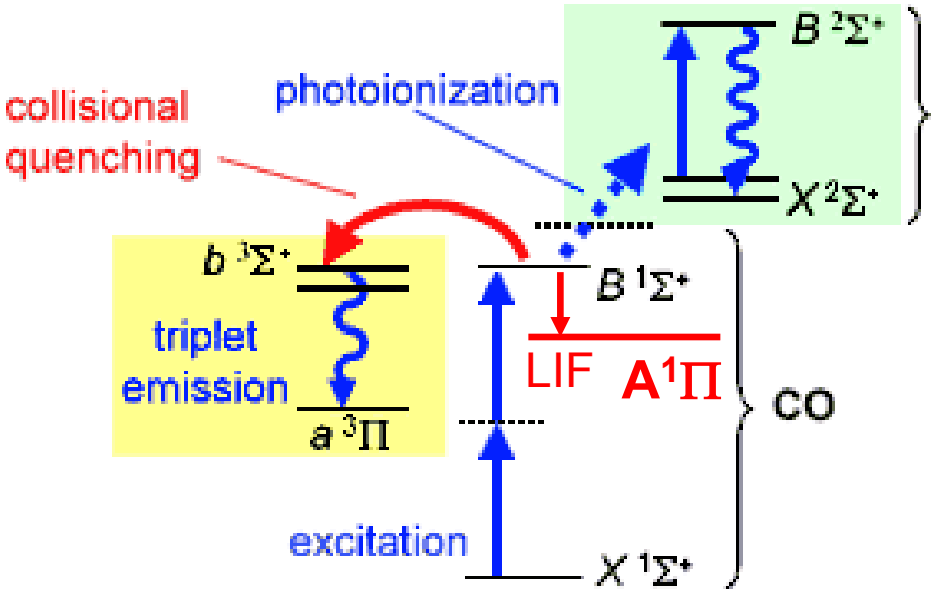
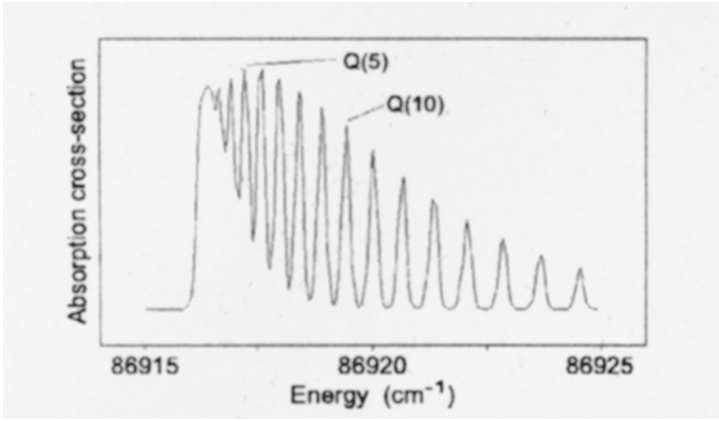
CO LIF

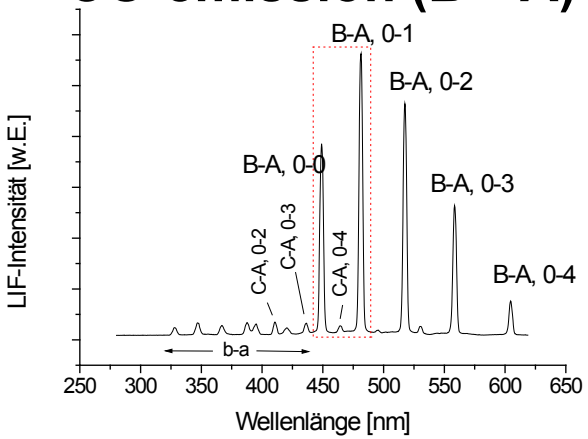
2-photon excitation



CO-absorption (B←←X)



CO-emission (B→A)



Coherent anti-Stokes Raman spectroscopy (1)

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- Non-linear polarization $P_i = \varepsilon_0 \left(\chi^{(1)}_{ij} E_j + \chi^{(2)}_{ijk} E_j E_k + \chi^{(3)}_{ijkl} E_j E_k E_l + \ldots \right)$

$\approx 10^{0}$ $\quad \approx 10^{-12}$ $\quad \approx 10^{-23}$

P_i : Polarization

E_i : Electrical field

$\chi^{(n)}$: Susceptibility of n-th order

⇨ Non-linear effects are observable only at high electrical field strength

⇨ Pulsed LASER is prerequisite

In Gases : $\chi^{(2)} = 0$

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CARS: energy and momentum conservation

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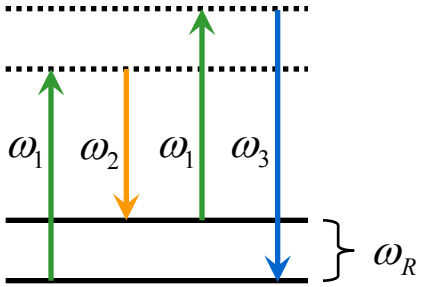
- Pictorial view of CARS

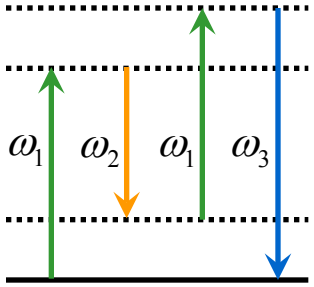
Energy balance: $\omega_3 = 2\omega_1 - \omega_2$

Pump laser

Stokes laser

CARS signal (anti-Stokes)



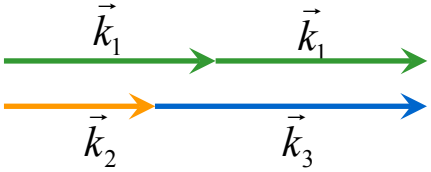


Selection rules

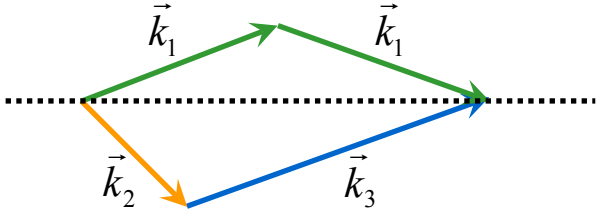
$\Delta J = 0, \pm 2$

$\Delta v = 1$

Momentum balance: $\vec{k}_3 = \vec{k}_1 + \vec{k}_1' - \vec{k}_2$ **Termed phase matching**



Co-linear CARS



BOX CARS: preferred, higher spatial resolution

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CARS: phase matching

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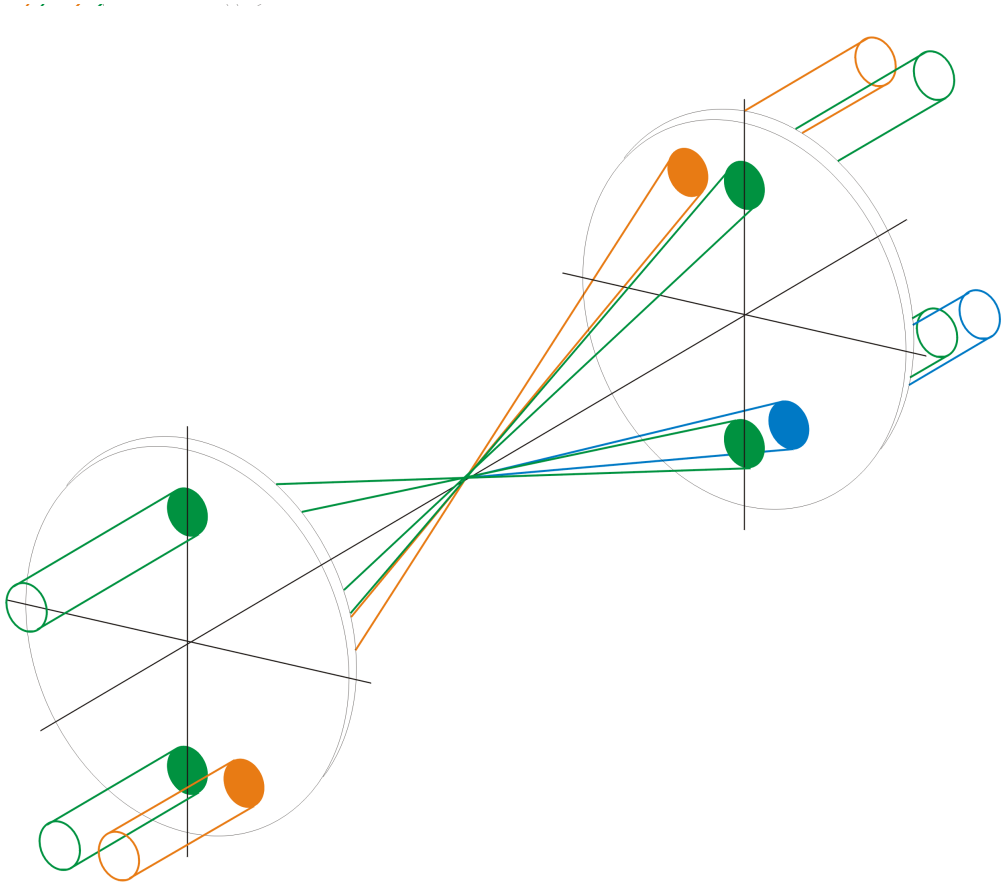
- Realization of phase matching
  - **Pump laser: 532 nm (frequency-doubled Nd:YAG)**
  - **Stokes laser: 607 nm (broadband dye laser)**
  - **CARS signal: 473 nm**



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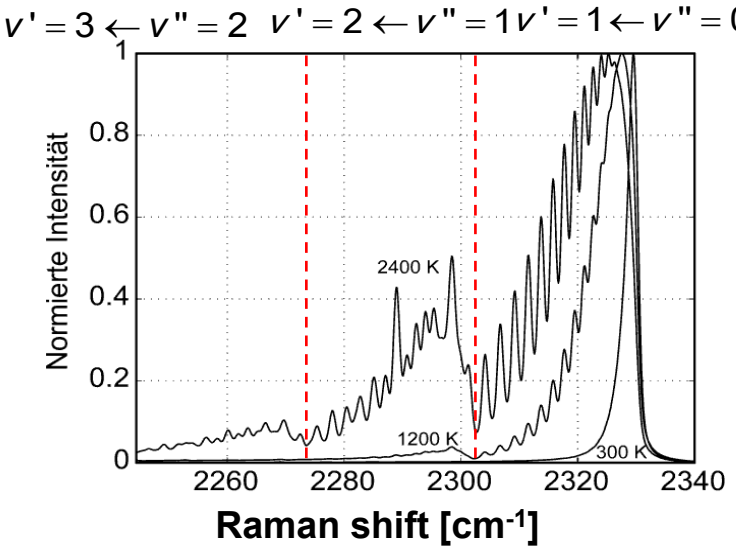
CARS: thermometry

- Typical application in turbulent flames: ro-vibronic N_2-broad band CARS



⇨

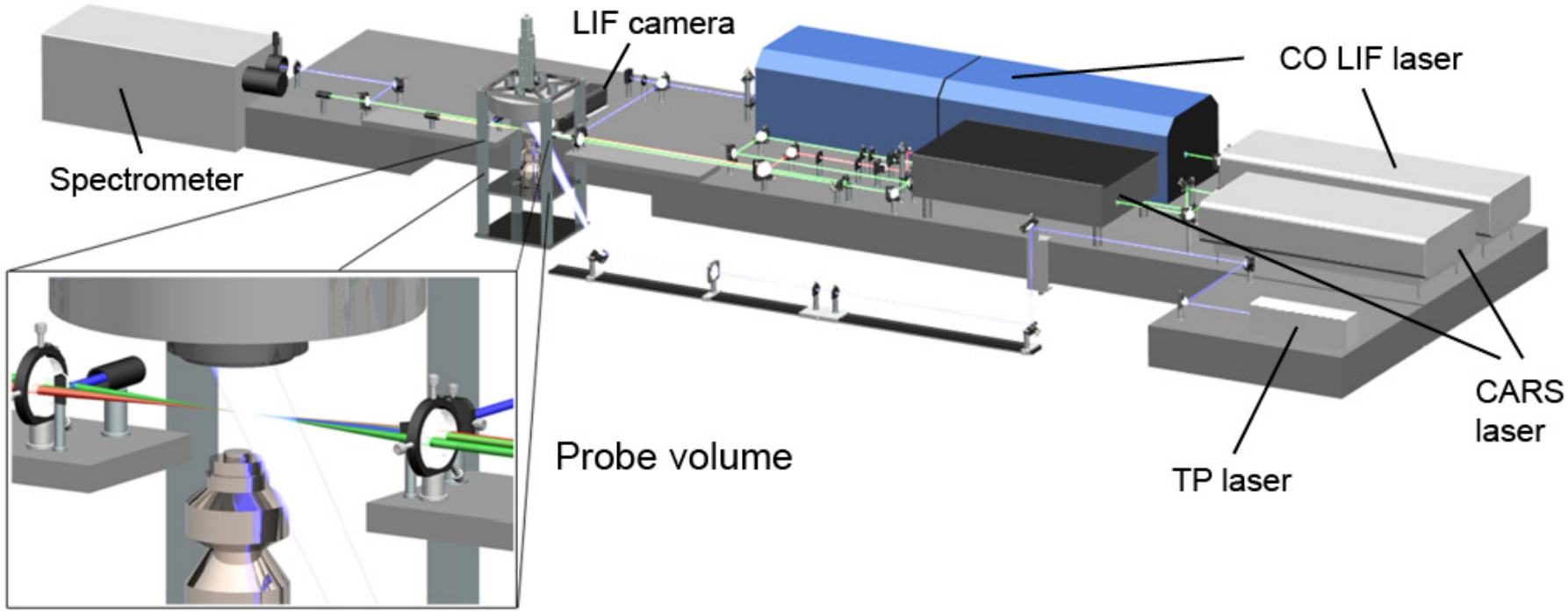
Temperature obtained by fitting CARS spectrum to experimental spectrum

Temperature information is contained in line-strength~N_i^2 (in χ^3-tensor)

Based on Boltzmann distribution

$$\frac{N_i}{\sum_i N_i} = \frac{g_i e^{-E_i/kT}}{\sum_i g_i e^{-E_i/kT}}$$

Combined CARS – CO LIF – setup



Measurement techniques

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Fluid Velocity	Flame Front Position	Fluid Temperature	CO Concentration
Particle Image Velocimetry (**PIV**)	Planar **LIF** of OH molecule Flame front from OH gradient	Coherent Anti Stokes Raman Spectroscopy (**CARS**)	Two Photon **LIF** of CO radical
2 D/2 Components Repetition Rate: 10 kHz	2 D Repetition Rate: 10 kHz	0 D Repetition Rate: 10 Hz	0 D Repetition Rate: 10 Hz
Resolution: Wall-nearest loc.: ~0.4 mm	Resolution: Wall-nearest loc.: ~0.1 mm	Resolution: Wall-nearest loc.: **~0.05 mm**	Resolution: Wall-nearest loc.: **~0.1 mm**
Precision and Accuracy: similar to PIV far from walls	Uncertainty: ±0.05 mm	Precision: 2.5 – 8%	Precision: 8 – 11 % Accuracy: ≤20% in most regions
Challenge: Too few particles very close to wall, beam steering	Challenge: Noisy signal, IRO blurring	Challenge: Resolution in beam wise direction, 0D **extension to 1D**	Challenge: Spatial resolution, calibration, 0D extension to 1D feasible

simultaneously

simultaneously

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Outline

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- Motivation of Flame-Wall Interaction (FWI) Research
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  - Flame dynamics of turbulent flames
  - Thermo-chemical states
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    - Flame surface density
    - Mean reaction rate modelling
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    - Laminar flames
    - Turbulent flames

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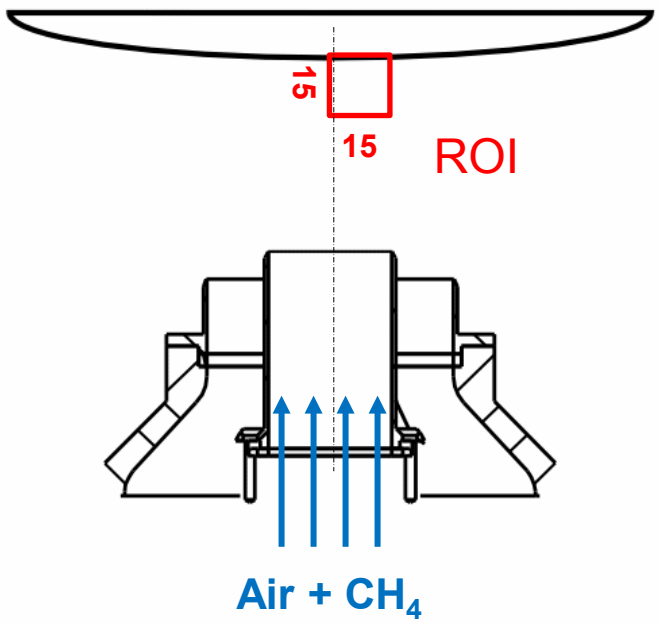
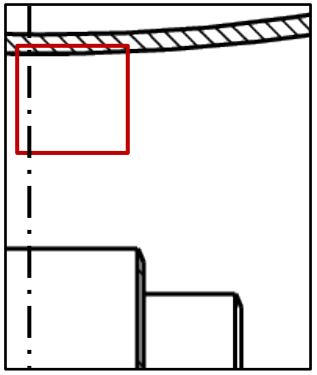
Unsteady flame-wall interaction



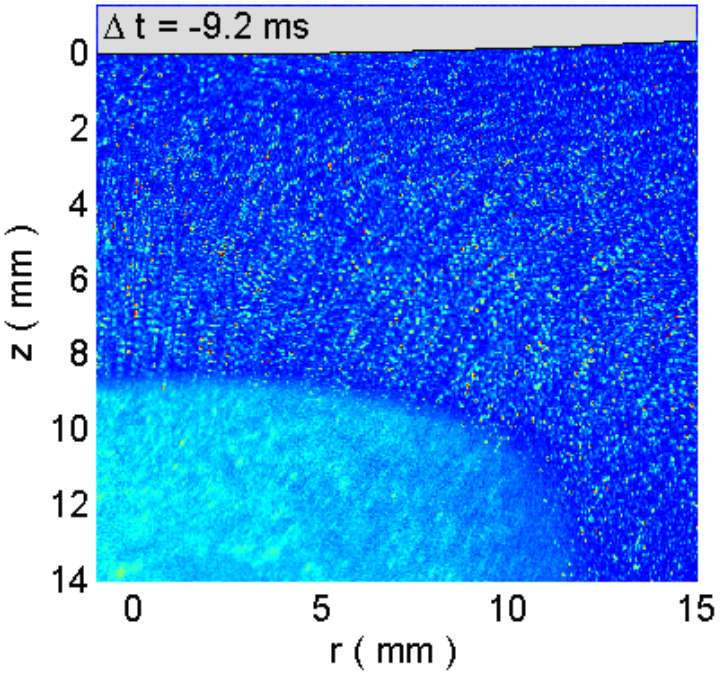
- Flame is **ignited** by a laser spark over the nozzle
- Flame **propagates** towards the wall
- **Re = 5000, 10 000; Φ = 0.83, 1.0;** with and w/o **TG**
- Region of interest (ROI): **15 x 15 mm²**
- Measured: **CO, T, Velocity** and **Flame Front Position**
- **Unburned gas** between flame and wall

Laminar flame propagation and wall impingement

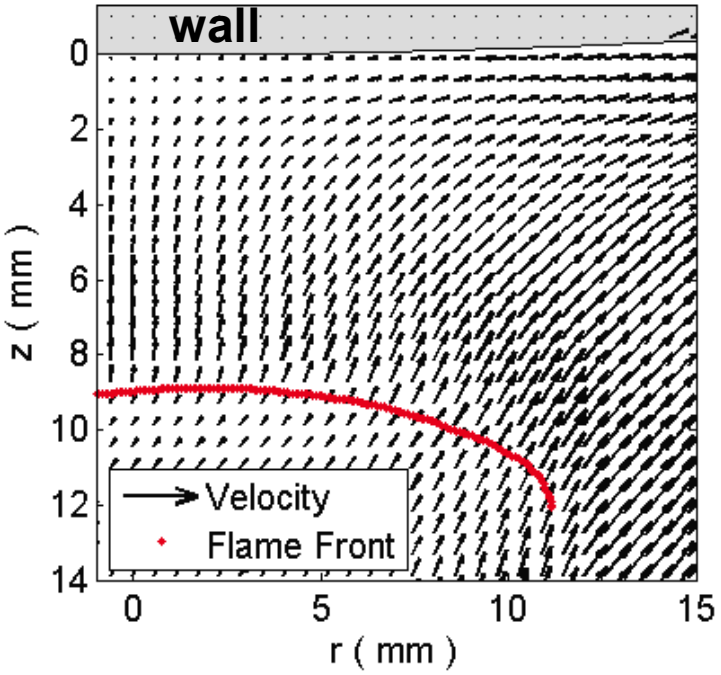


- Φ = 0.83
- Frame rate 10 kHz

Chemiluminescence (and Mie scattering)



2C flow field and flame front (PIV&OH-PLIF)



Unsteady flame-wall interaction
(Re = 5000, Φ = 1.0, with and w/o TG)

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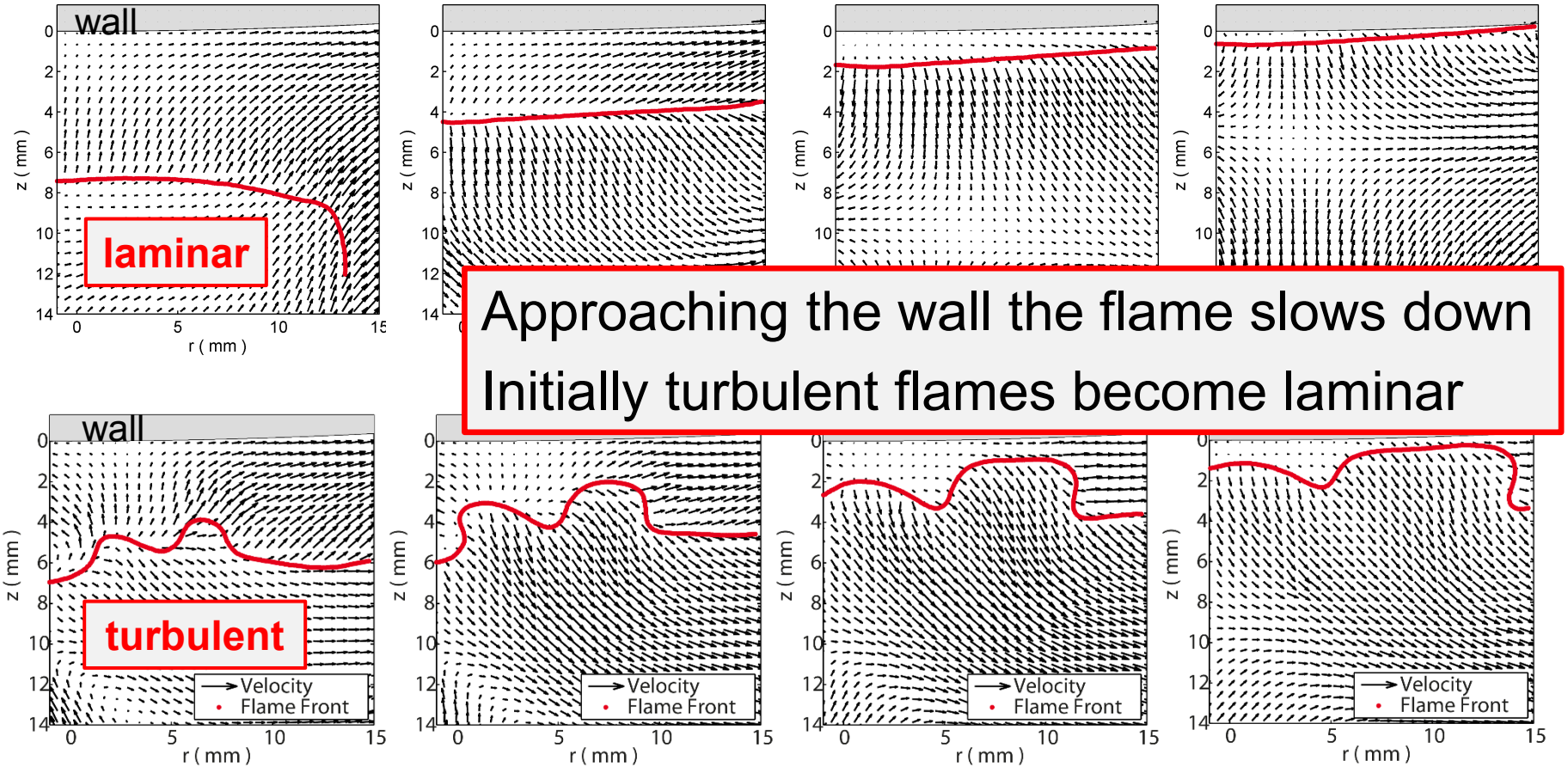

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Phase-resolved temperature and CO concentration measurements for HOQ - laminar

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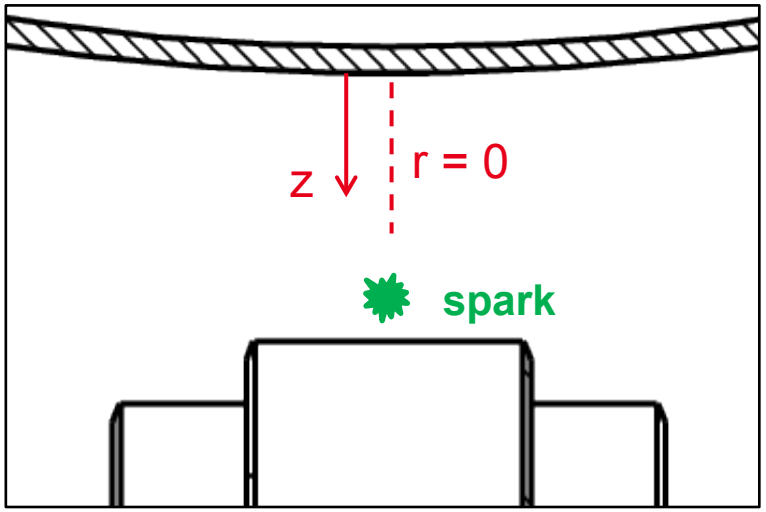
- Laser spark 2 mm above nozzle
- Phase-fixed CO-T-measurements relative to spark
  - 6 probe volume (PV) locations spanning from $0.1 \leq z \leq 1.7$ mm
  - Focus on near wall region
- Time delay: Variation of time in steps of $\Delta t = 100$ µs
- 200 single-shots at each PV
- Example: $\Phi = 0.83$, Re = 5000



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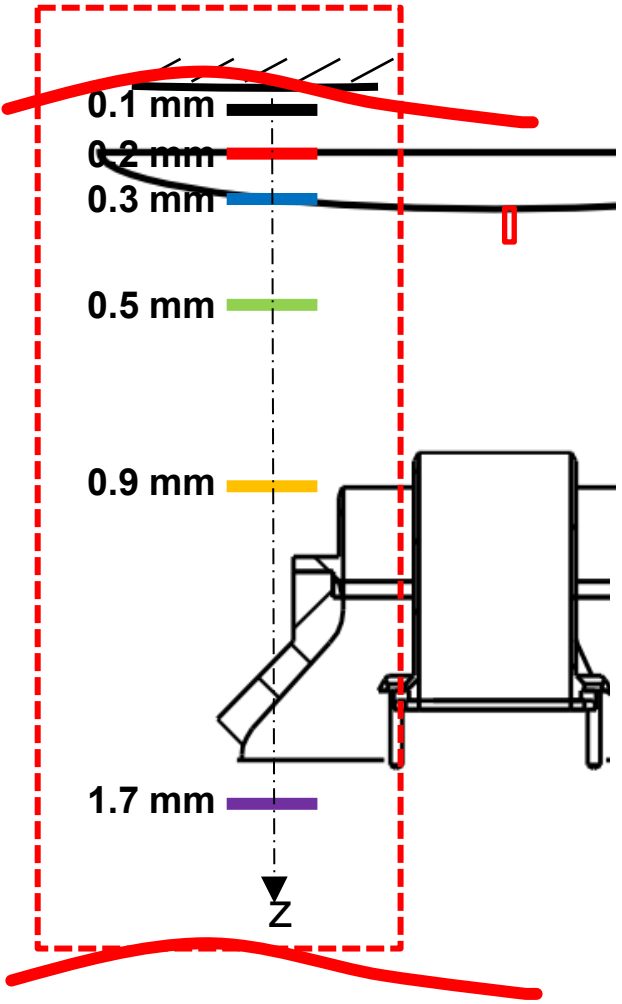
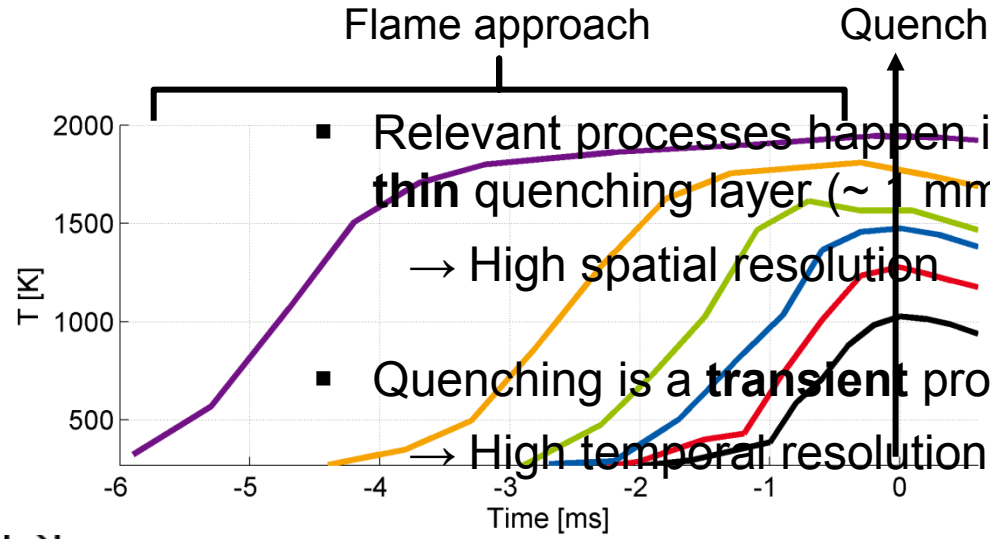
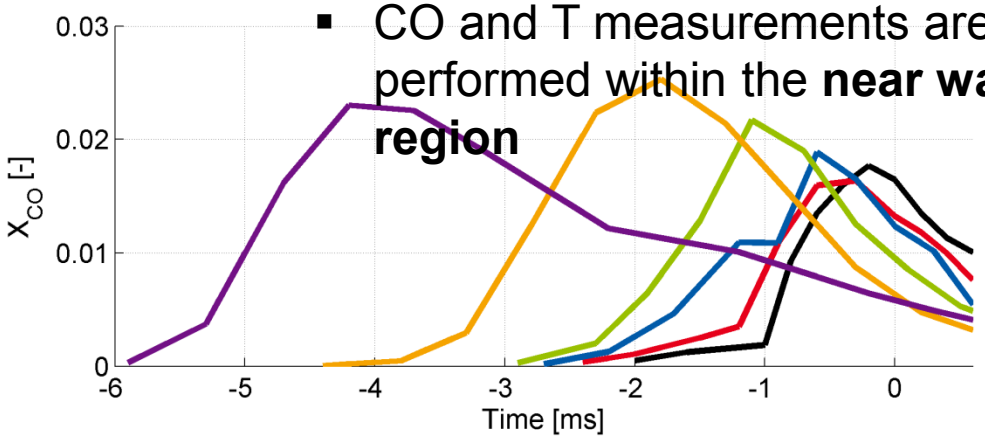
Time-resolved temperature profiles for HOQ - laminar





- Relevant processes happen in a **very thin** quenching layer (~ 1 mm)
  → High spatial resolution
- Quenching is a **transient** process
  → High temporal resolution

Temp. (CARS)



- CO and T measurements are performed within the **near wall region**

CO conc. (LIF)

Laminar thermo-kinetic states
(Re = 5000, Φ = 1.0, w/o TG)

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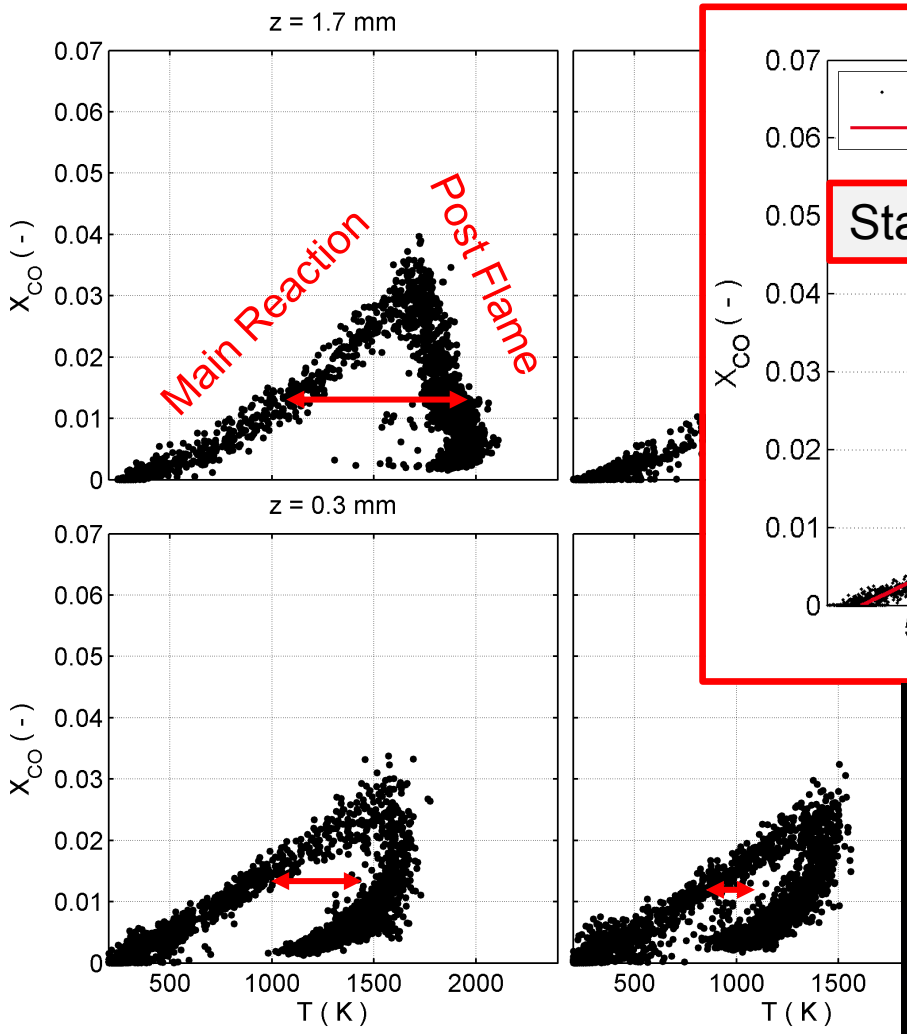

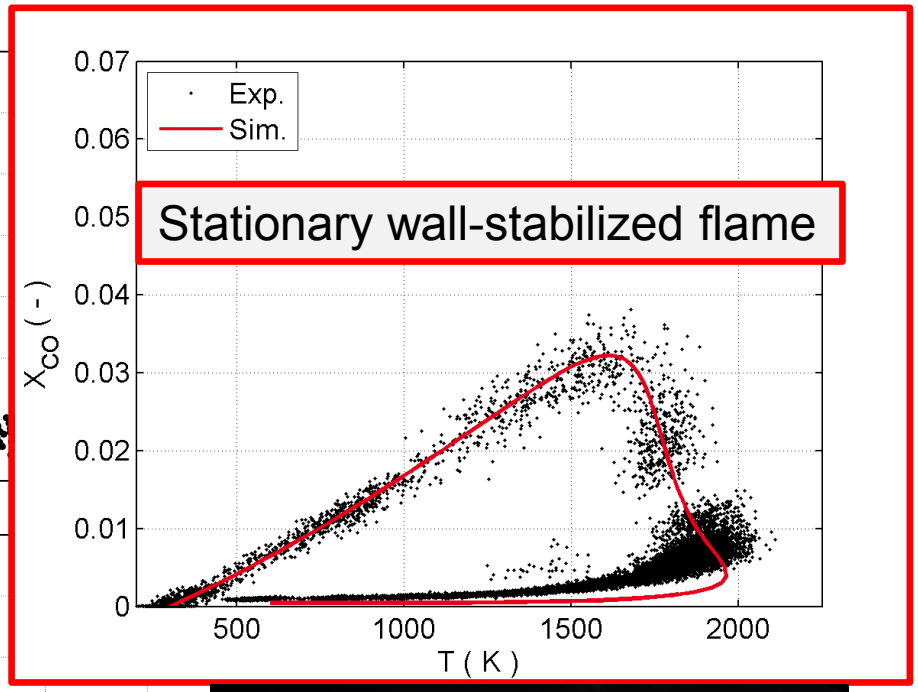

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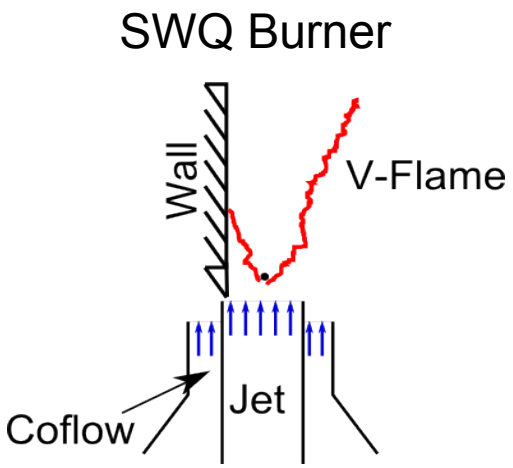

Laminar vs. turbulent flame

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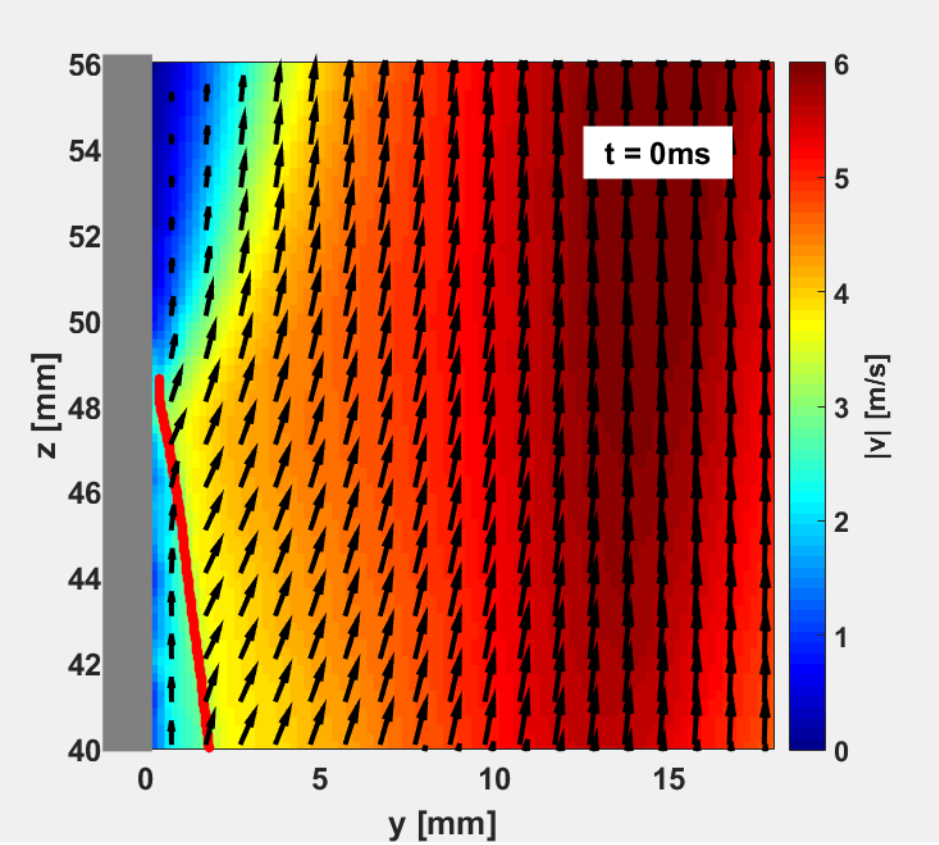
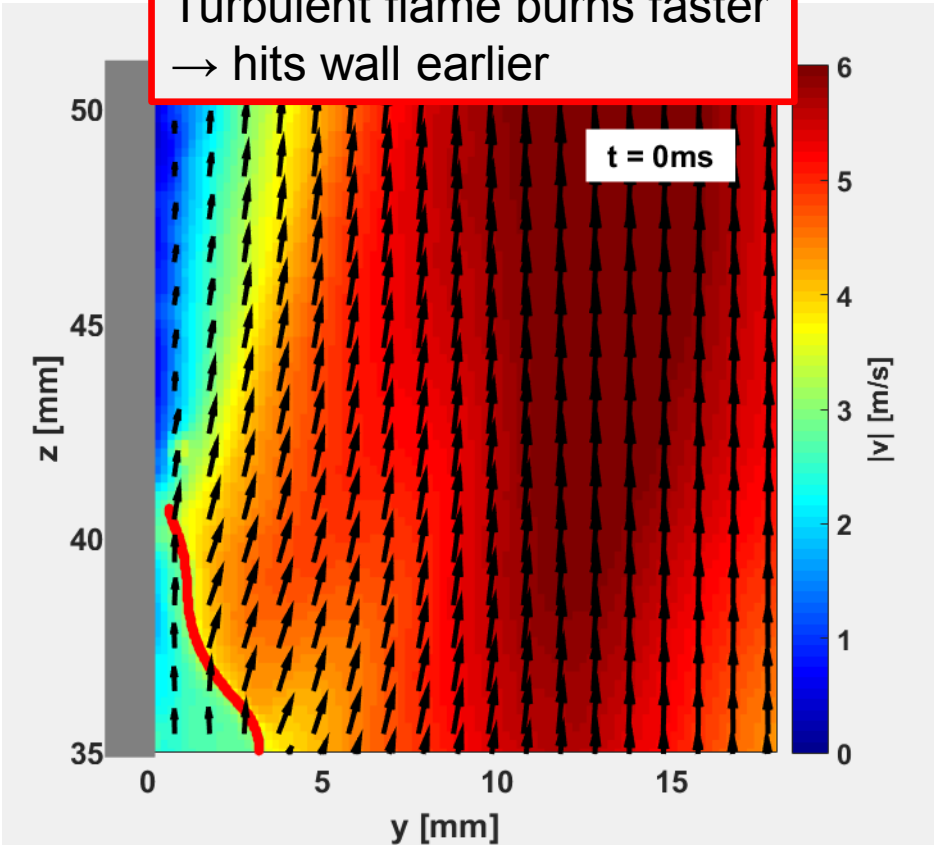
laminar, φ = 1.0



turbulent, φ = 1.0

Turbulent flame burns faster
→ hits wall earlier



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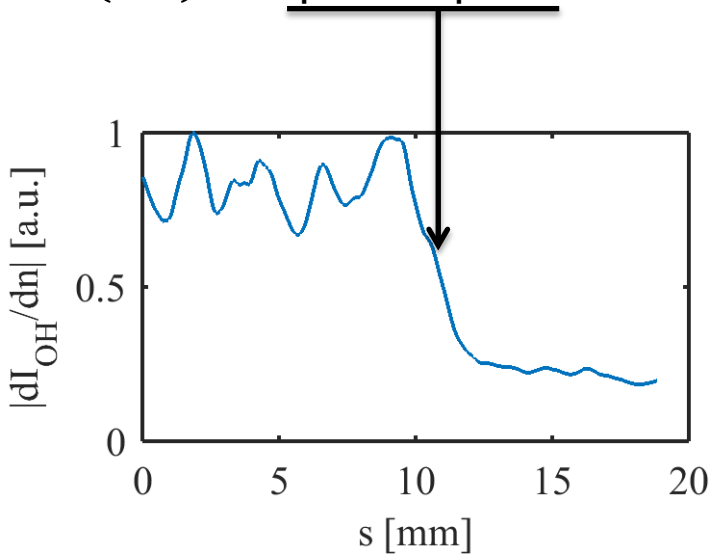
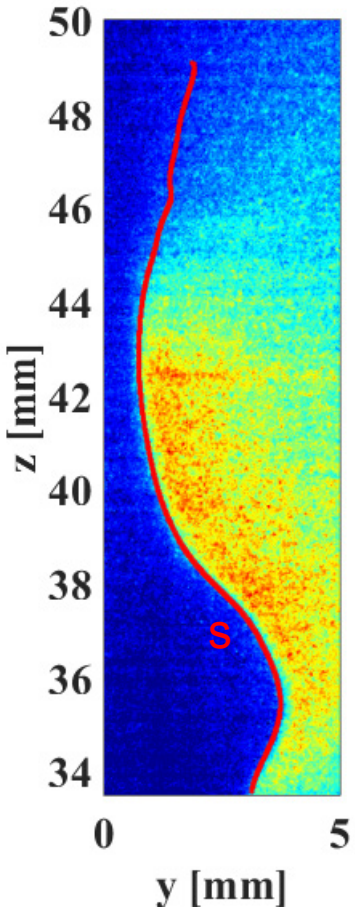
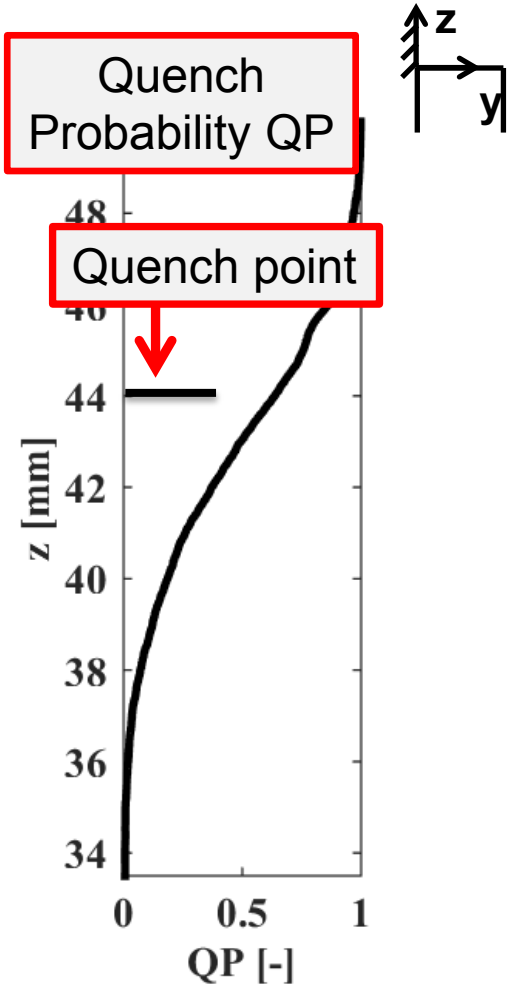
Post-processing of OH PLIF

- Flame front detection:
  I. Canny-Edge-Filter
  II. Threshold of flame-normal $\nabla(OH)$ for quench point







Flame brush and quench probability

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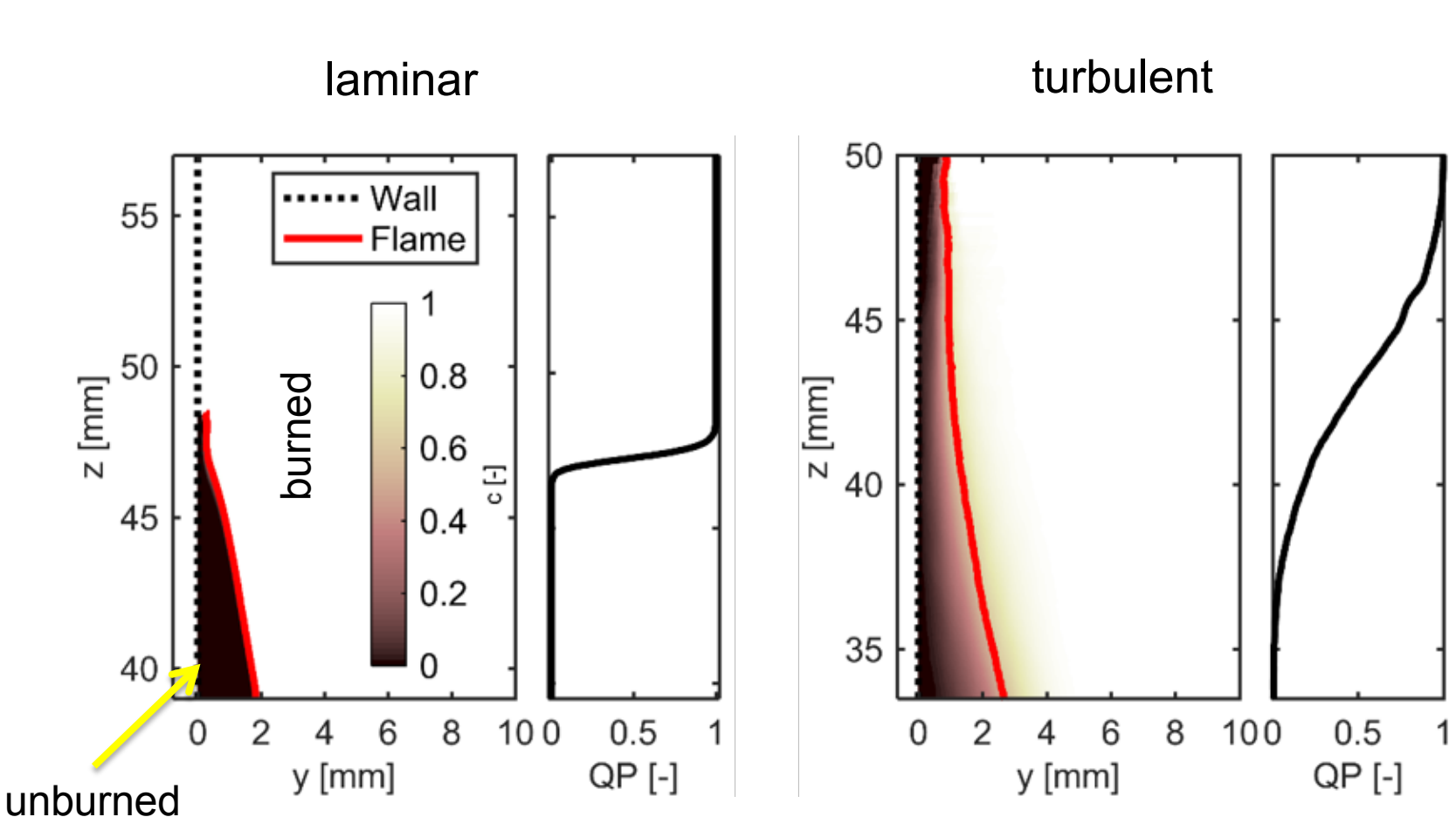

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Modelling of turbulent premixed flames

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- Flame surface density (FSD) model requires mean reaction rate $\overline{\dot{\omega}_R}$:
  1. turbulent flame → ensemble of laminar flamelets
  2. flame-flow interaction → local consumption speed s_l * flame surface density Σ

Density and fuel mass fraction of unburned mixture – **known**

$$\overline{\dot{\omega}_R} = \overbrace{\rho_1^0 \, Y_1^0} s_l \Sigma$$

OH PLIF & PIV

OH PLIF

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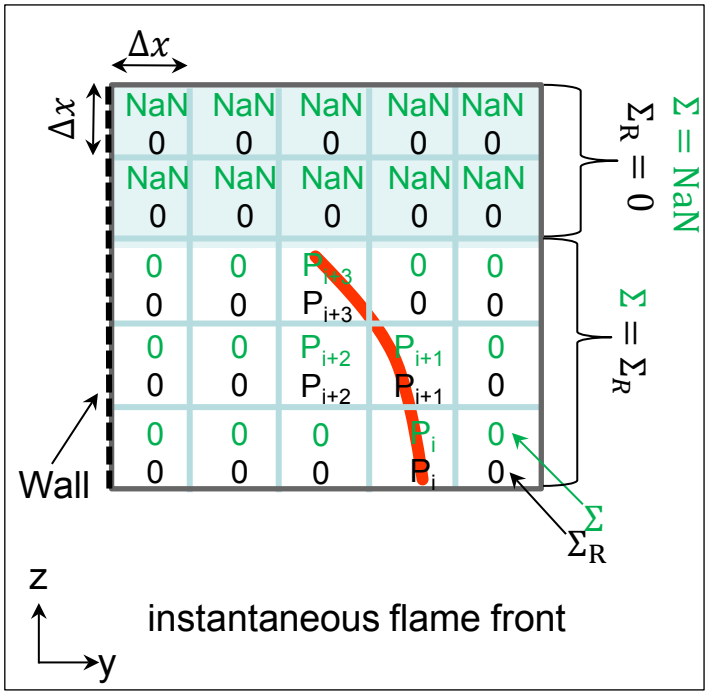
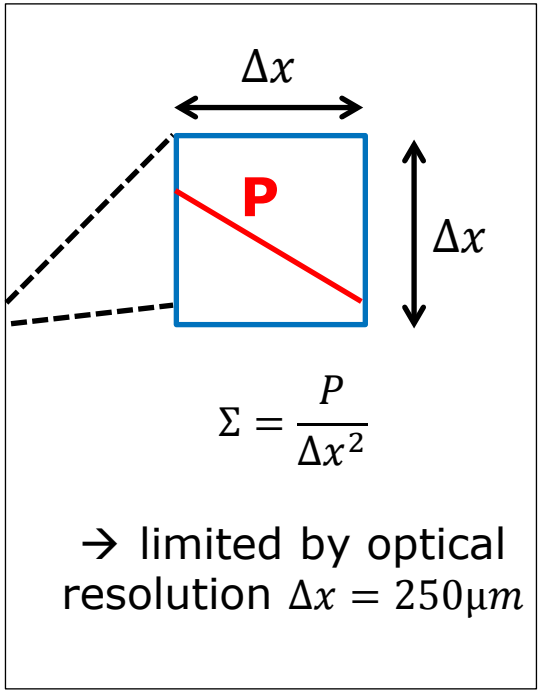
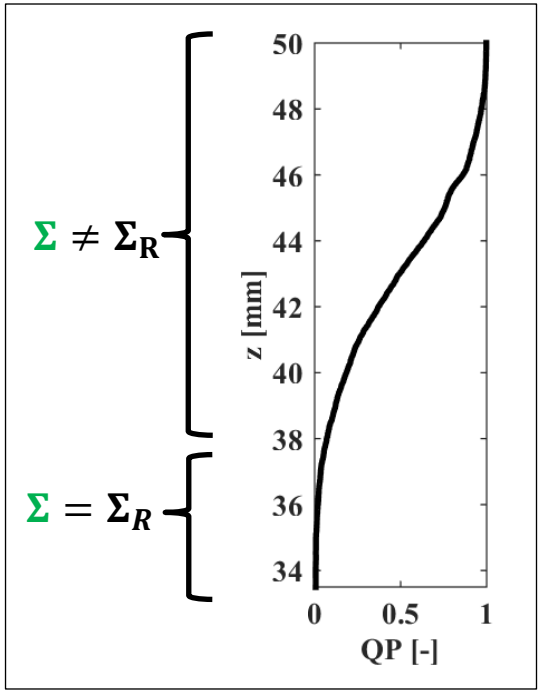
Flame surface density – definition







Σ ignores quenching
Σ_R considers quenching

Probability of quenching as function of height z over nozzle exit

Flame surface density – results

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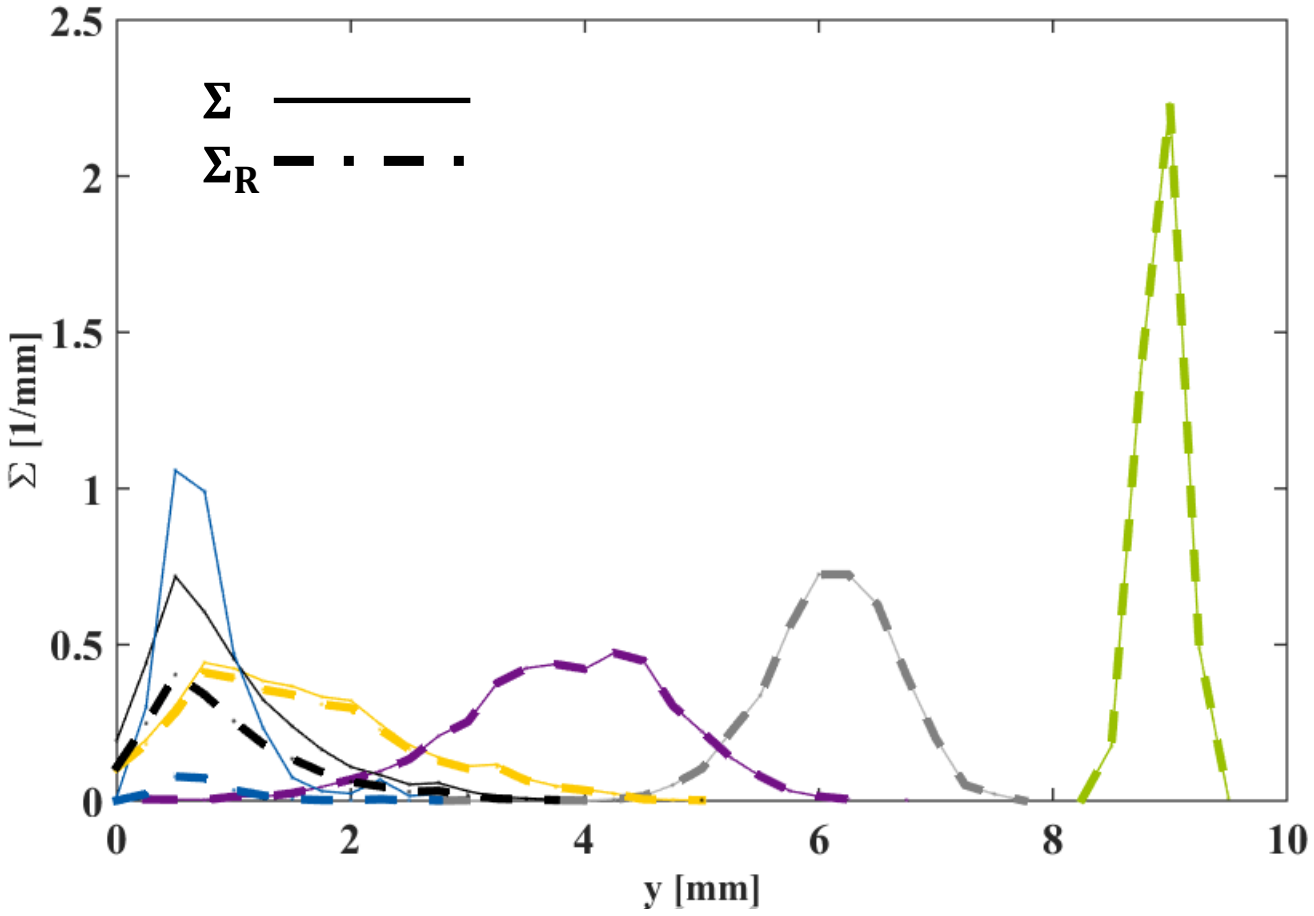
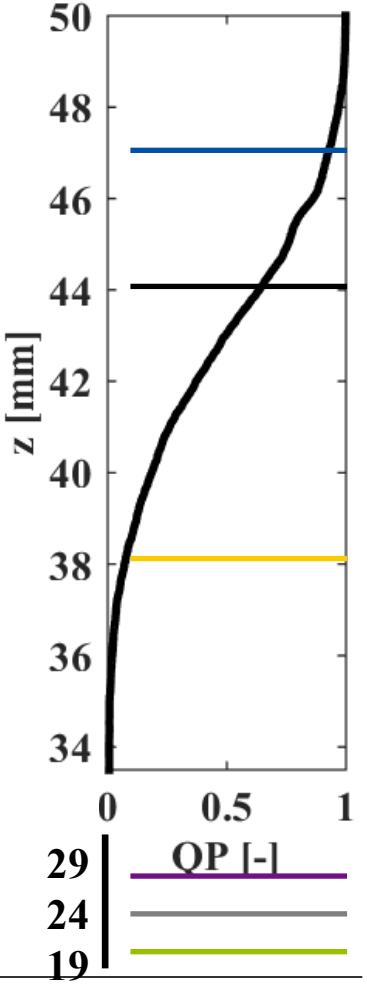
TG1, φ = 1, Re = 5000, CH_4





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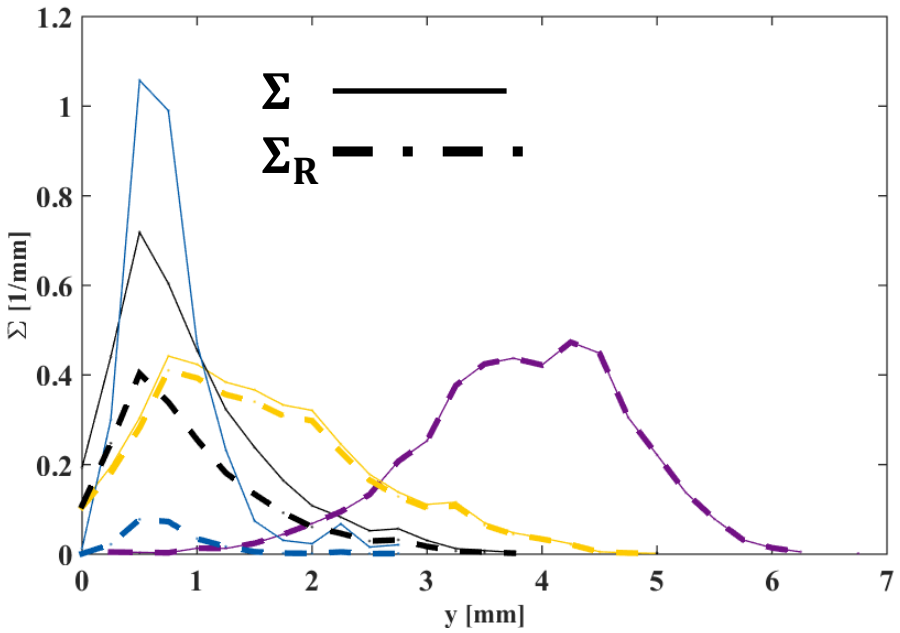
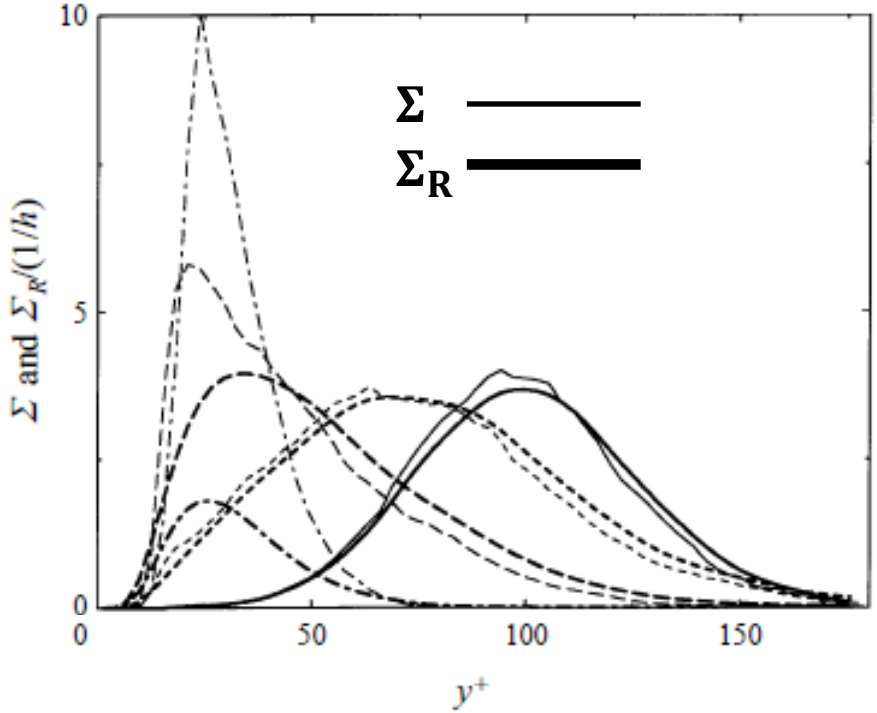
Flame surface density – comparison to DNS

RSM 2015: **EXP**
SWQ configuration

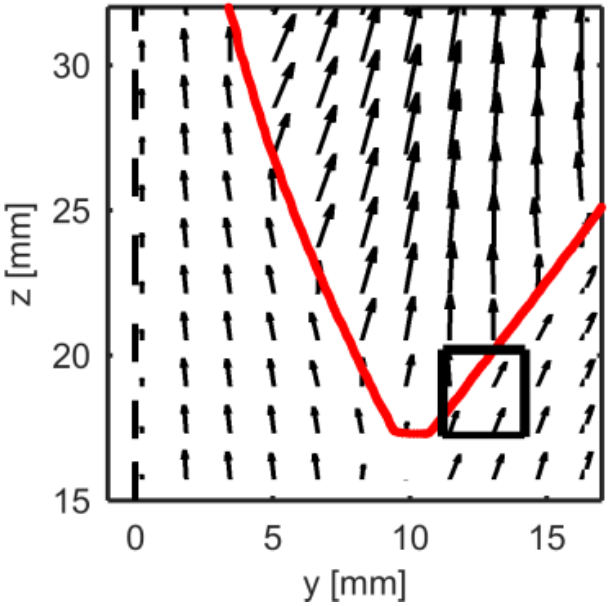


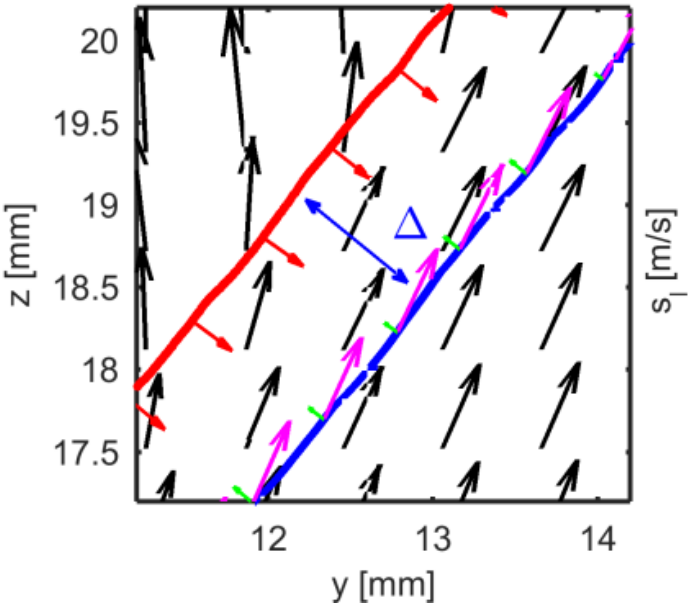
Bruneaux et al. 1997: **SIM**
HOQ configuration

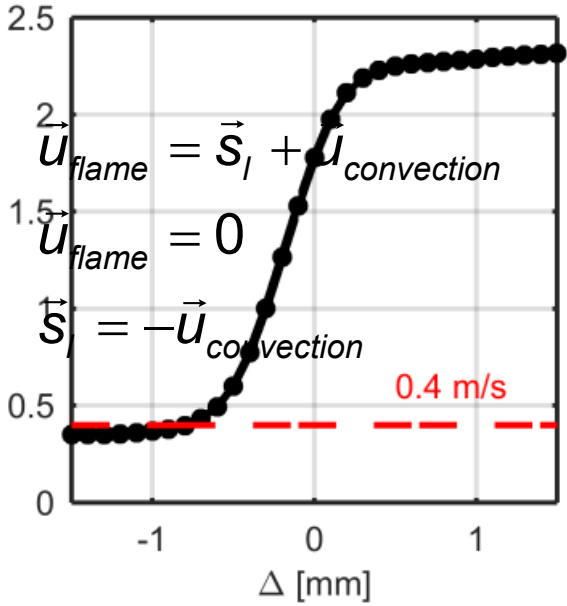


Flame consumption speed s_l - undisturbed

- s_l determined from **laminar configuration**
- Use of undisturbed flame branch





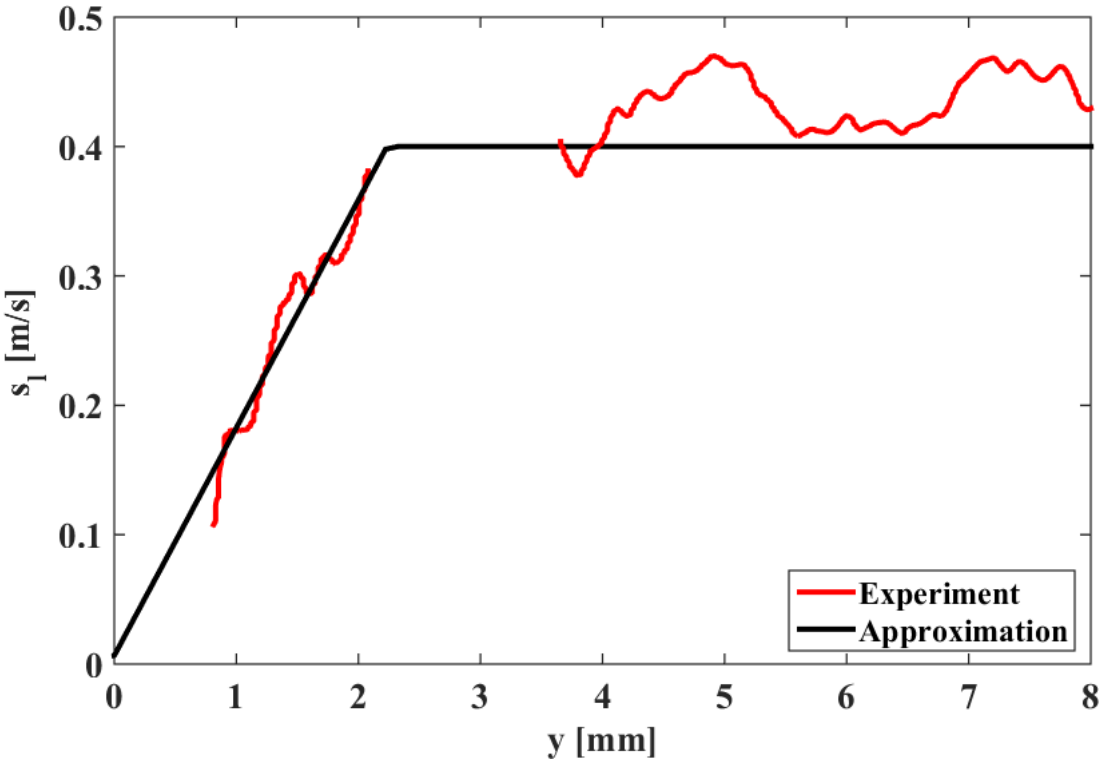


Green arrows: flame normal velocity components

1 mm ahead of flame front flame normal velocity matches laminar burning velocity

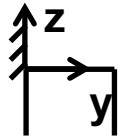
Flame consumption speed s_l - during wall approach

- wall closest point @ y = 1mm, because of s_l refers to unburnt mixture

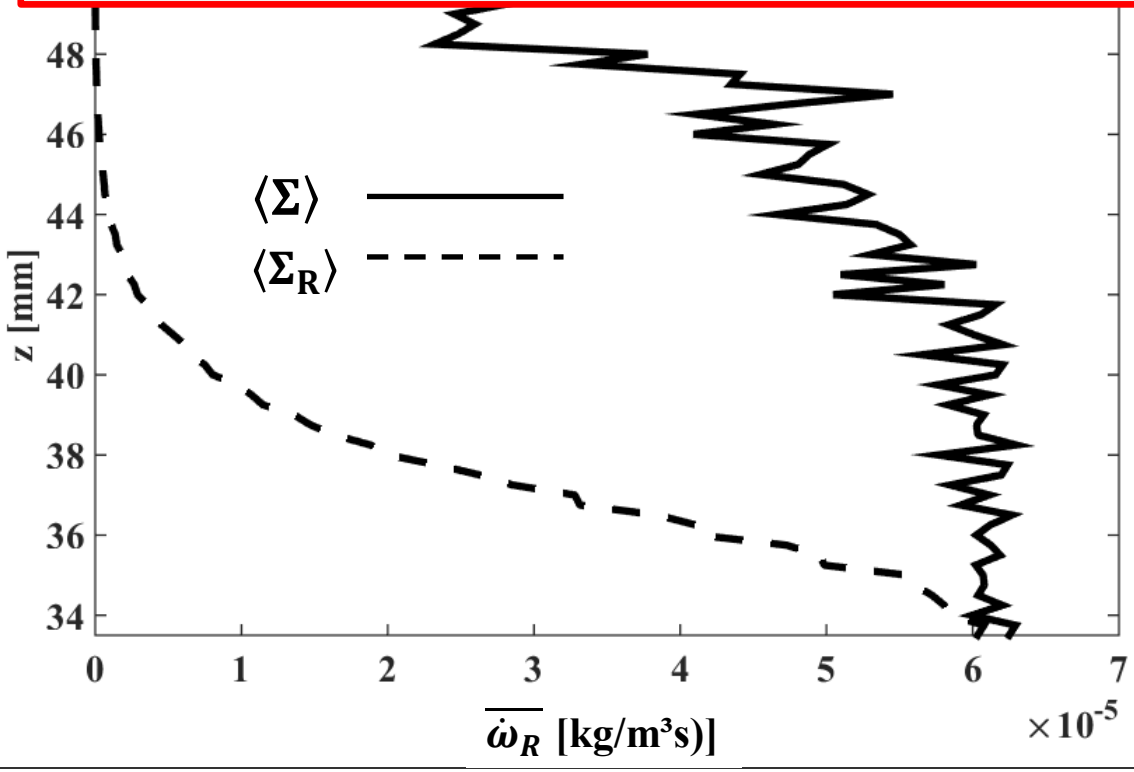


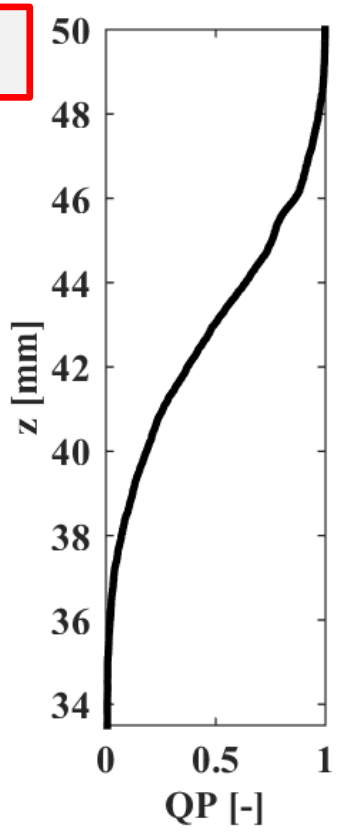
Mean reaction rate $\overline{\dot{\omega}_R}$

$$\overline{\dot{\omega}_R}(z) = \rho_1^0 \, Y_1^0 \langle s_l(y) \Sigma(y,z) \rangle$$



→ Mean reaction rate experimentally determined





Conclusions from PIV-OH PLIF measurements

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- **Impact of turbulence on FWI in SWQ-configuration:**

1. Analysis of FSD $\boldsymbol{\Sigma}$ reveals:
   - Relaminarization of the flame near the wall
   - "Reacting" FSD $\boldsymbol{\Sigma_R}$ necessary for correct SWQ description and modelling
2. Mean reaction rate $\overline{\dot{\omega}_R}$:
   - Deduced from flame surface density
   - Important quantity for modelling

- **Comparison to literature:**
  - Good agreement with HOQ DNS from Bruneaux (1997)
  - FSD $\boldsymbol{\Sigma_R}$ agrees qualitatively well with model based on velocity fluctuations from Watkins (1996) – see Jainski et al., PCI 2017

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} Jainski et al., Combust. Flame 2017

Laminar side wall quenching
(Re = 5000, Φ = 1.0, w/o TG)

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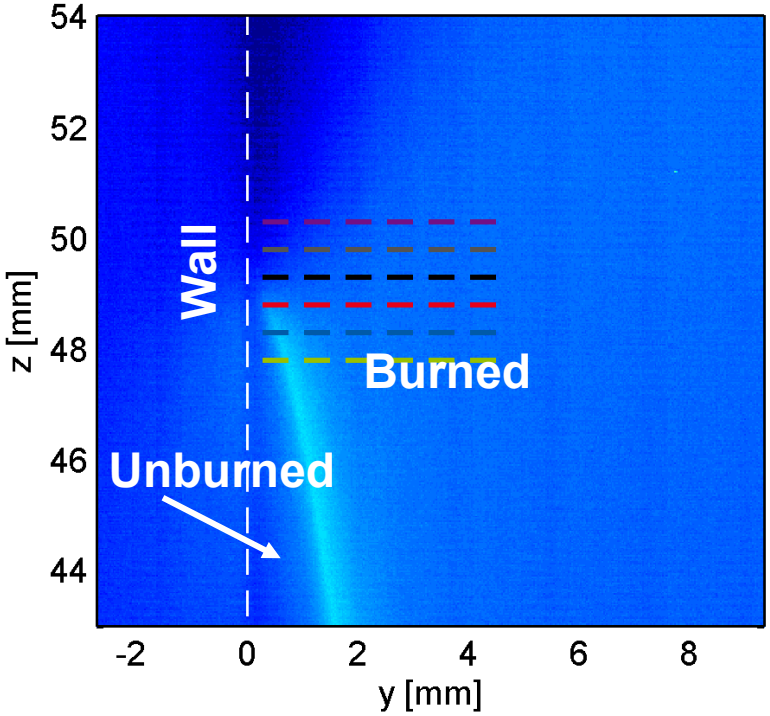
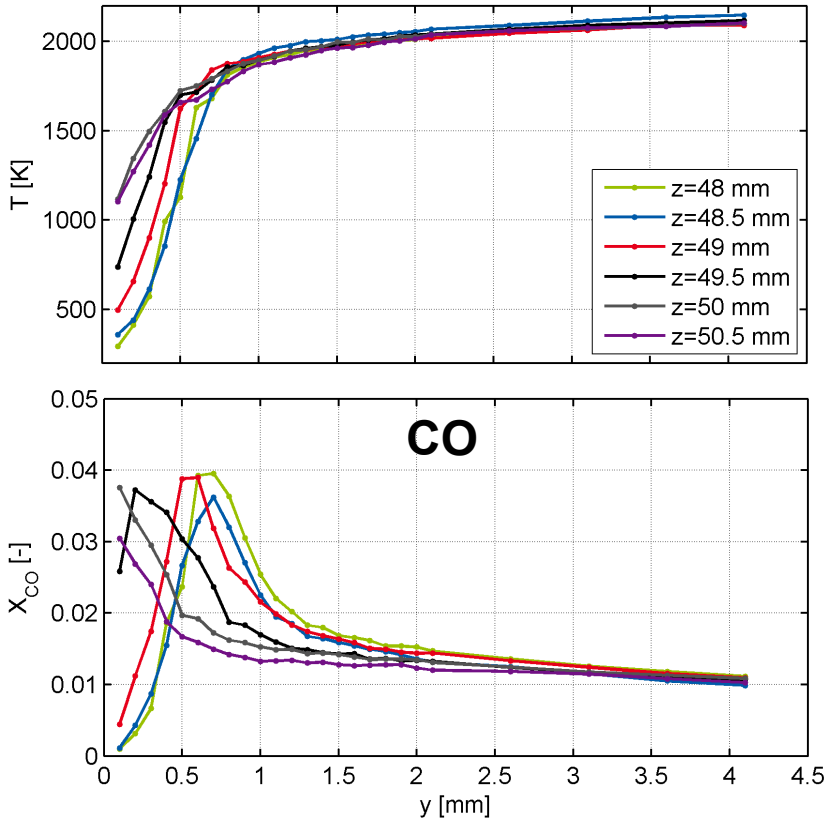
Flame Luminescence (Snap Shot)



Temperature



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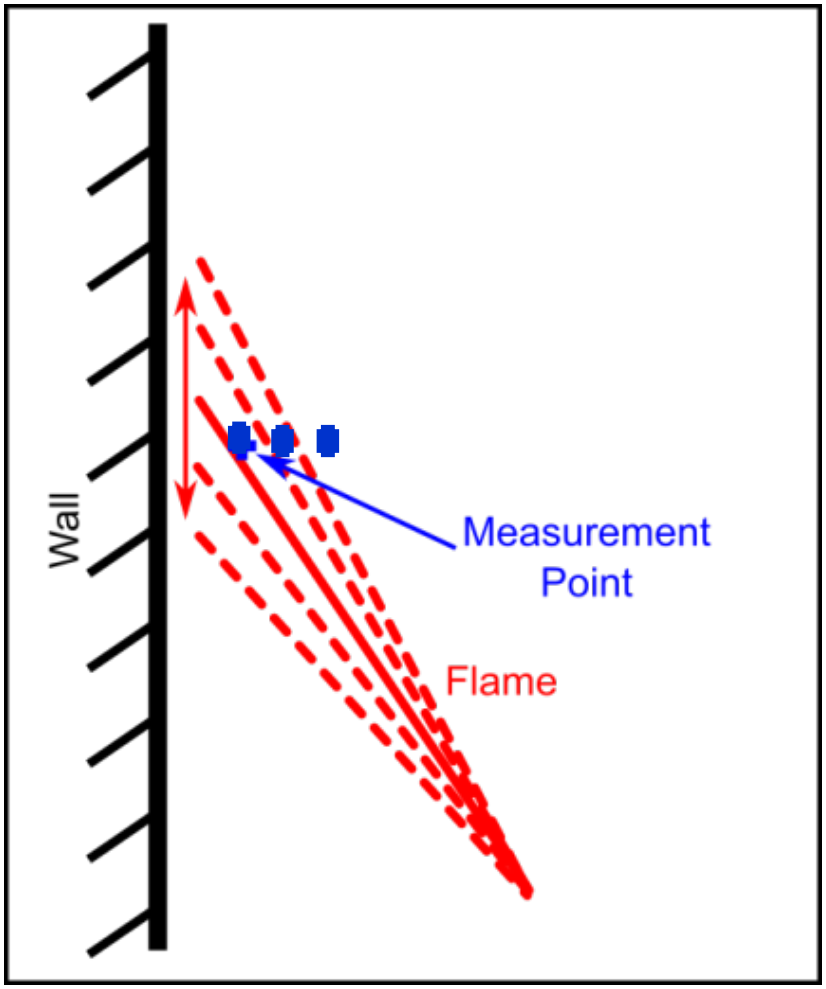
Space-fixed measurement of thermo-chemical states – laminar case



- Fixed axial positions spanning across the FWI-zone
- Scatter plots containing data from all distances to wall

Thermo-chemical states – laminar
(Re = 5000, Φ = 1.0, w/o TG)

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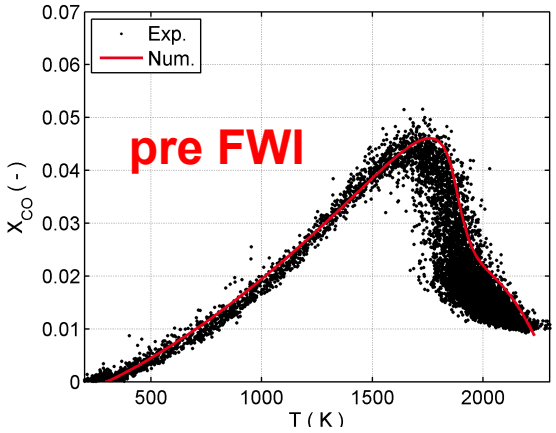
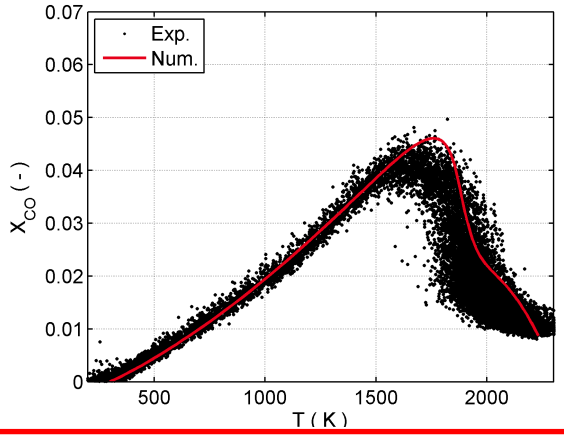
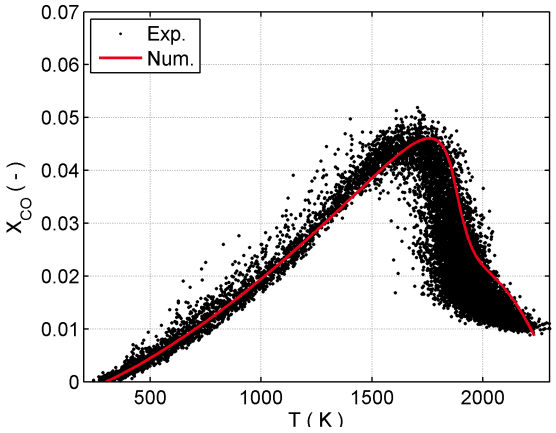
z = 48 mm



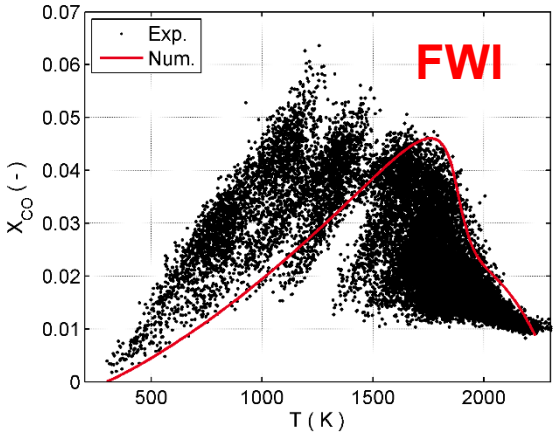
z = 48.5 mm



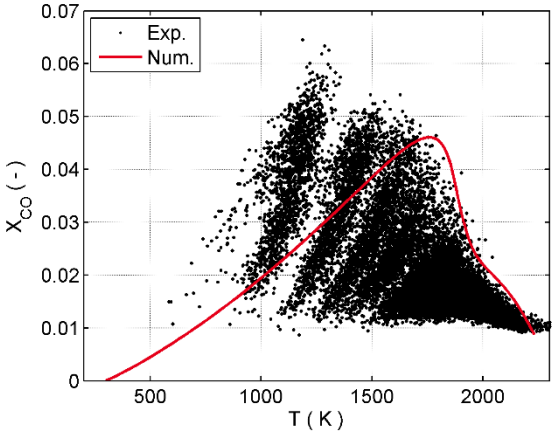
z = 49 mm



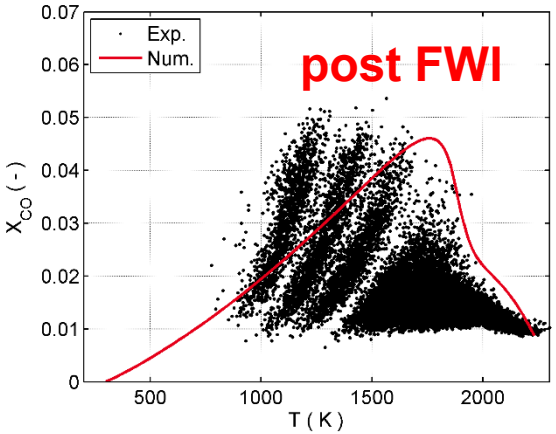
z = 49.5 mm



z = 50 mm



z = 50.5 mm



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Thermo-chemical states for z = 50.0 mm
(Re = 5000, Φ = 1.0, w/o TG)

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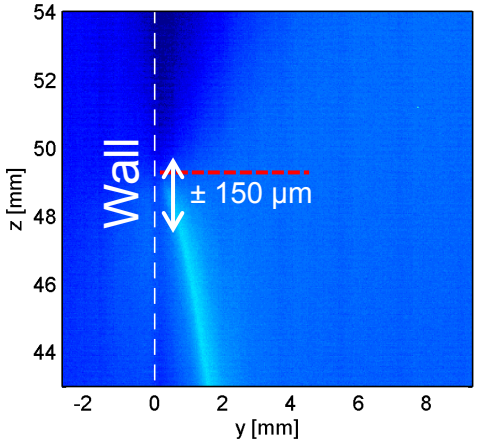
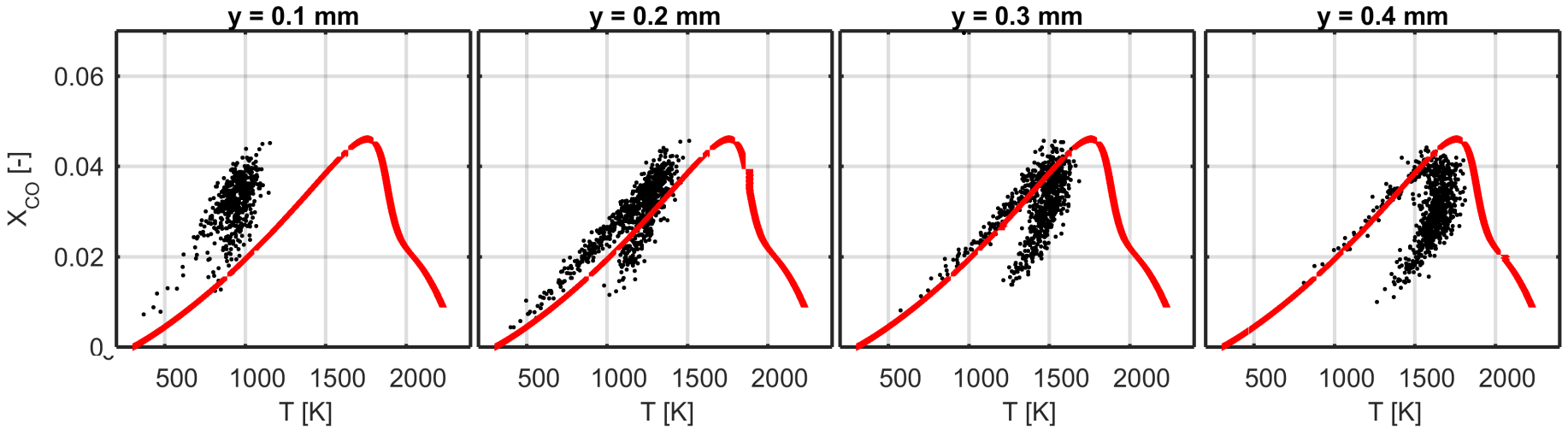


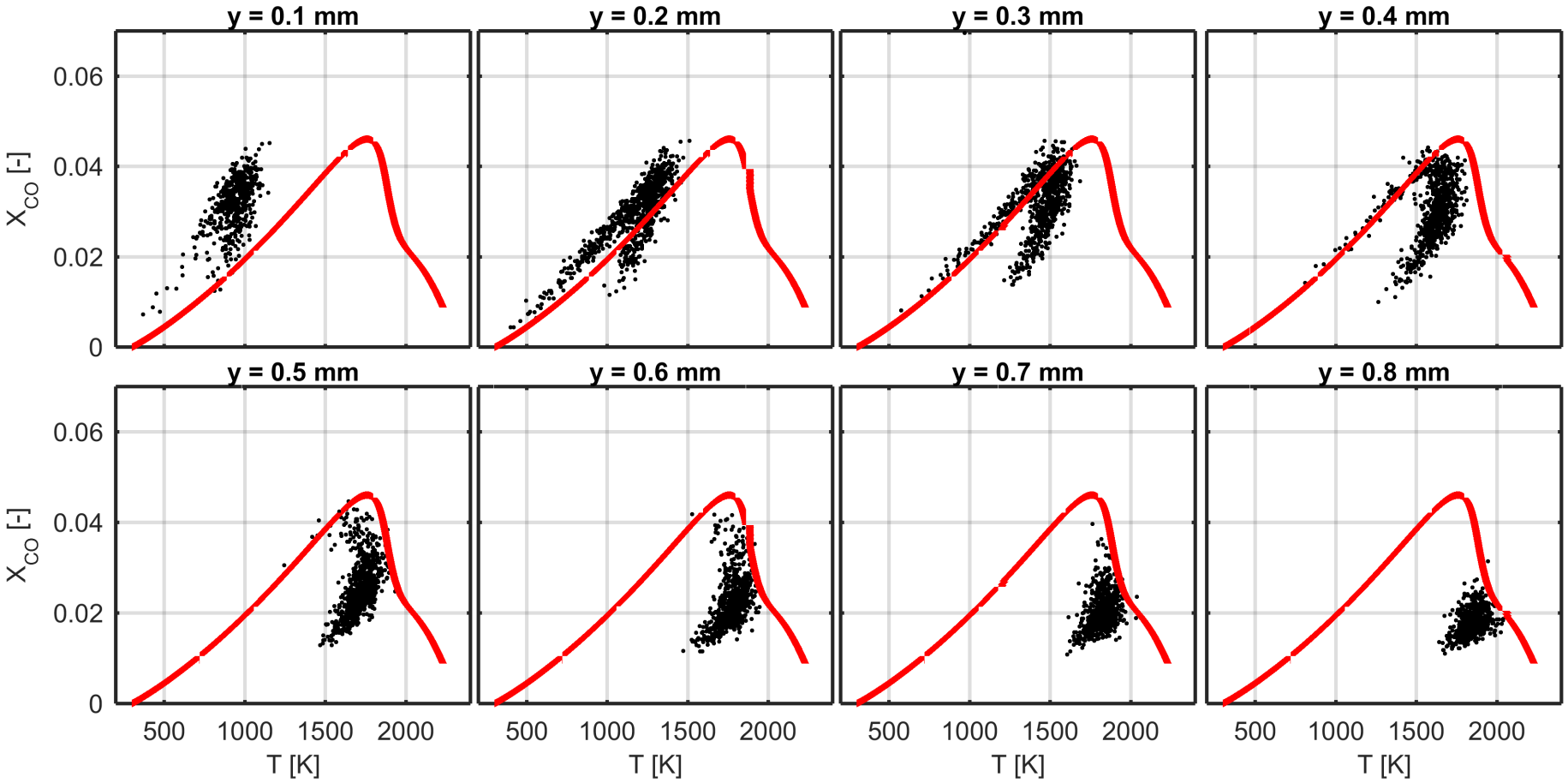
- Spatial **conditioning (axial & wall-normal)**
- Flame tip **fluctuates** up and down (± 150 µm)

→ Different **thermo-kinetic states** in one measurement point



RSM

Thermo-chemical states for z = 50.0 mm
(Re = 5000, Φ = 1.0, w/o TG)



Thermo-chemical states for z = 50.0 mm
(Re = 5000, Φ = 1.0, w/o TG)

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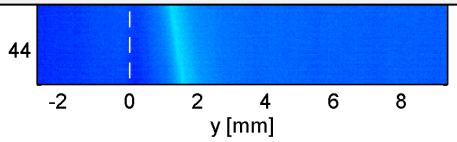
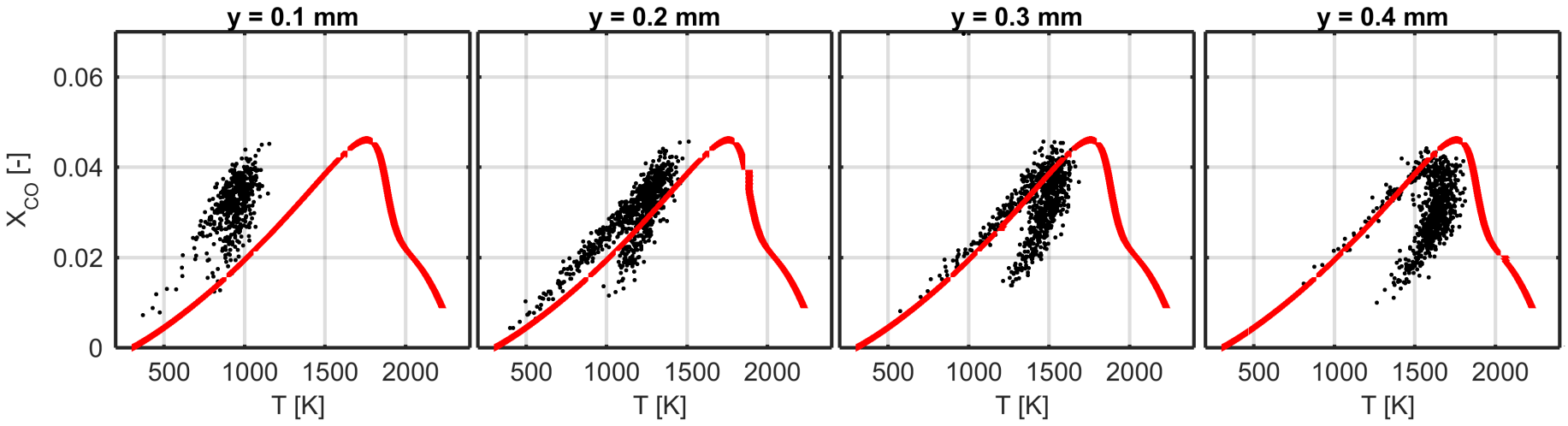
- **CO-consumption branch**: strongly influenced for wall distances y < 0.8 mm
- CO-production branch: influence starts for y ≤ 0.2 mm
- **Time-scales** of CO-consumption a factor of 100 larger than for CO-production

→ **Heat losses more pronounced for CO-consumption branch**



→ Different **thermo-kinetic states** in one measurement point



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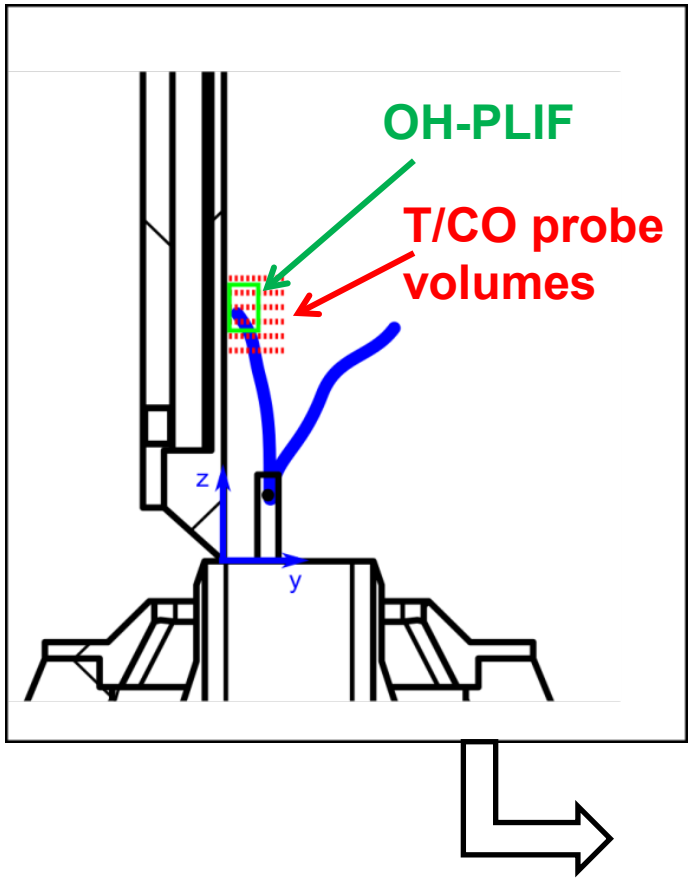
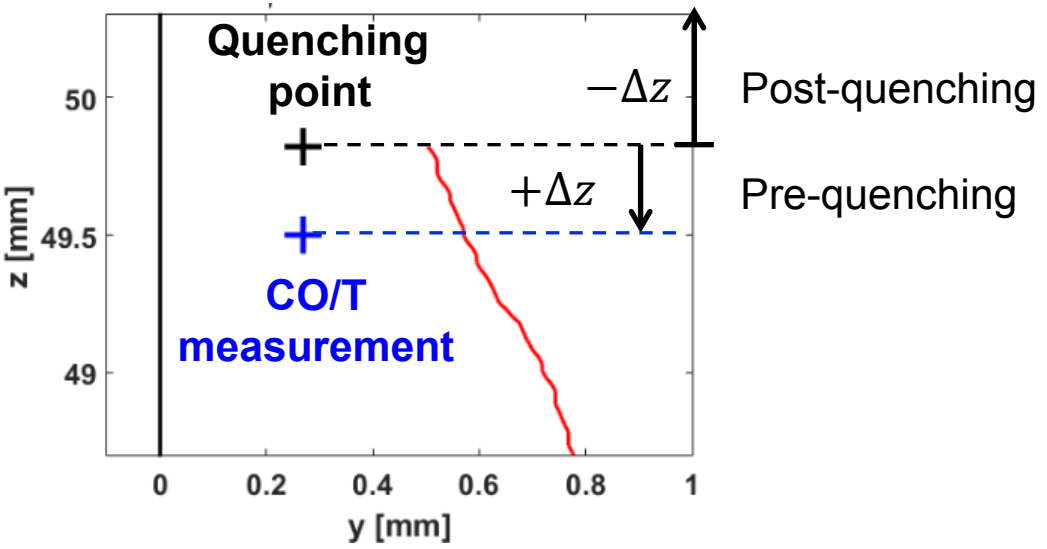
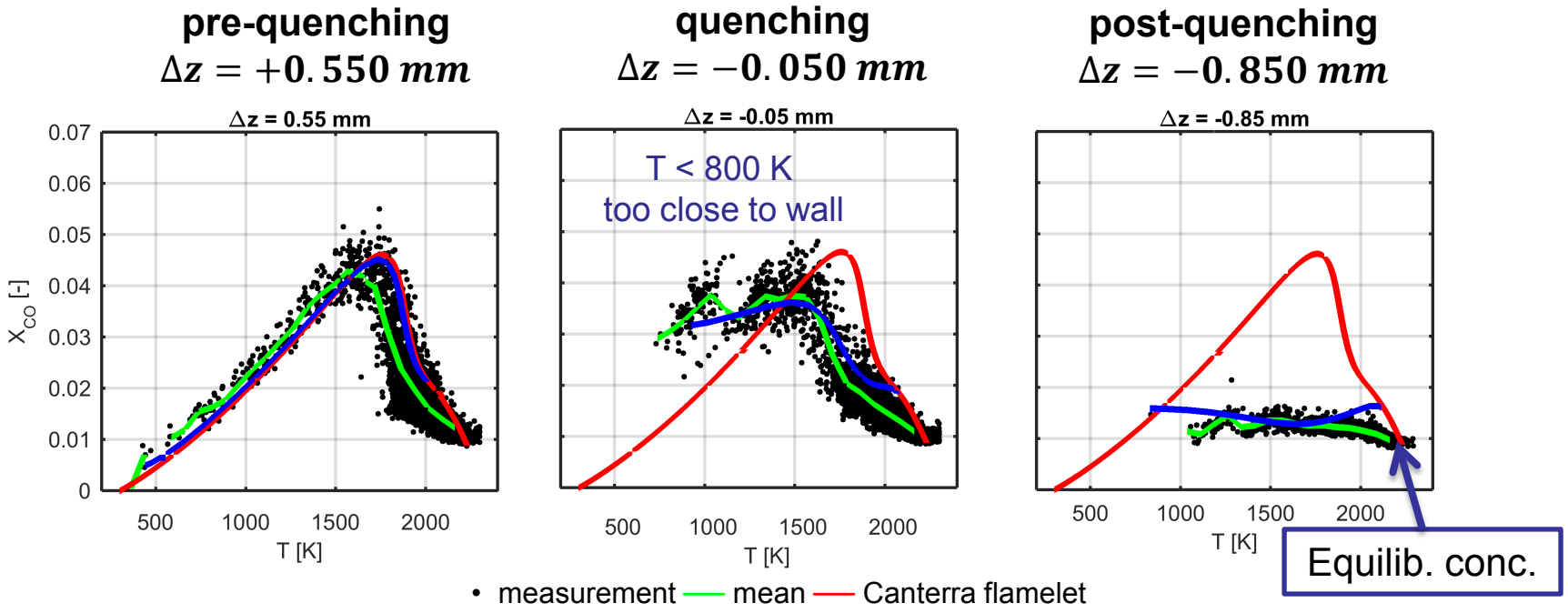
Analysis of thermo-chemical states relative to quenching point – flame fixed





Conditioning on quenching – flame fixed analysis



Pre-quenching: undisturbed flame

Quenching and **post-quenching**: strong deviation from undisturbed flame

S. Ganter, G. Kuenne, J. Janicka: Comparison to 2D-DNS reveals **dominance of diffusion** over kinetic effects that cause this observation

Time scale analysis

Time scale of heat transfer[1]

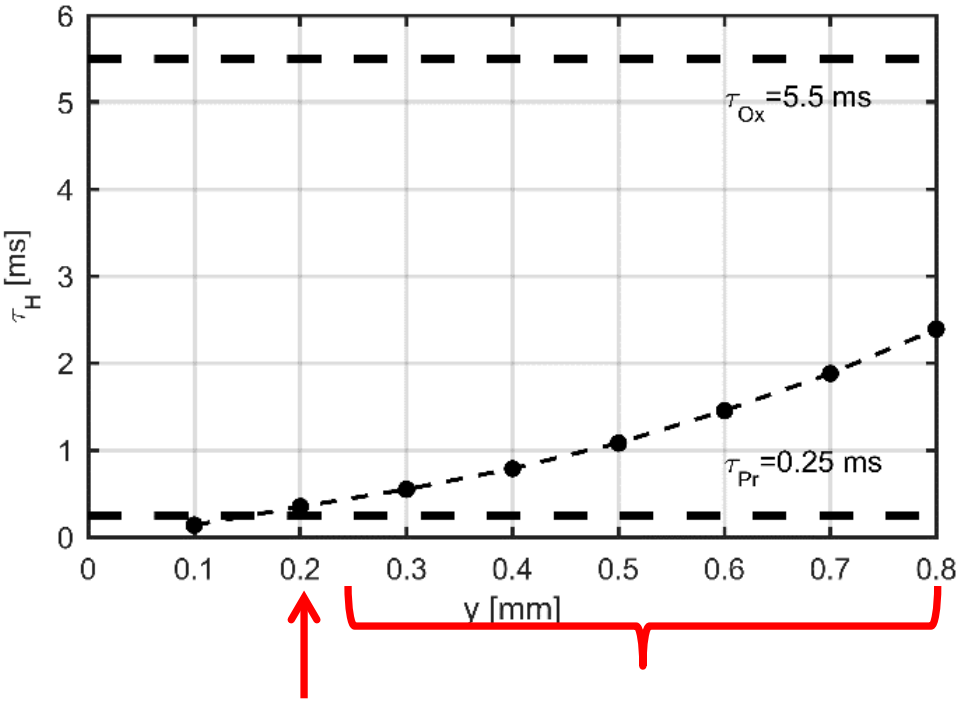
$$\tau_H = \frac{L^2}{\lambda}\rho c_p,$$

- L represents the wall-normal distance *y*
- λ heat conductivity

Chemical time scales, from 1D calculations

CO production $\tau_{Pr} = 0.25\ ms$

CO oxidation $\tau_{Ox} = 5.5\ ms$



Heat transfer faster than CO prod and ox

Heat transfer faster only than CO ox; CO prod unaffected

[1] E. Marín, Characteristic dimensions for heat transfer, Latin-American Journal of Physics Education 4 (2010) 56–60

Mean quantities reveal significant differences between laminar and turbulent flames

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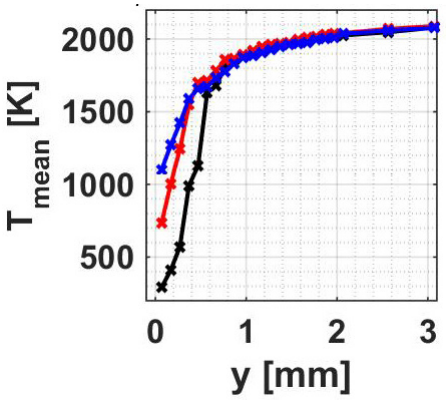
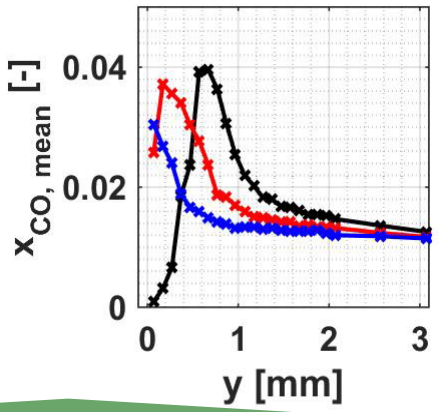
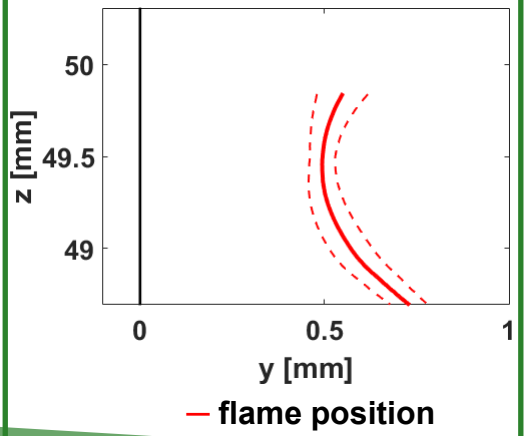
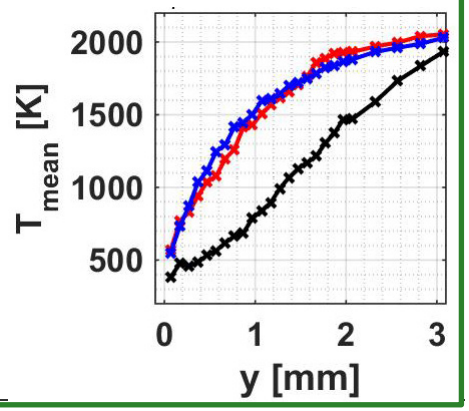
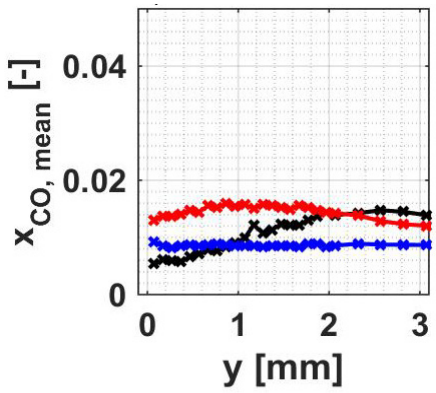
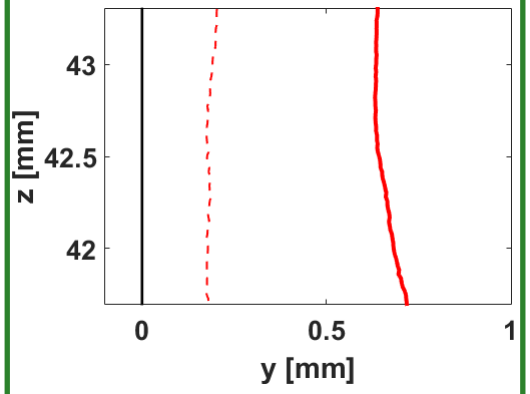
flames	temperatures (CARS)	CO concentrations	flame position (OH)
laminar flame $\varphi = 1$, Re = 5000 — pre-FWI — FWI — post-FWI			
turbulent flame $\varphi = 1$, Re = 5000 — pre-FWI — FWI — post-FWI			

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Turbulent flame – space fixed analysis
($\varphi = 1$, Re = 5000, with TG)

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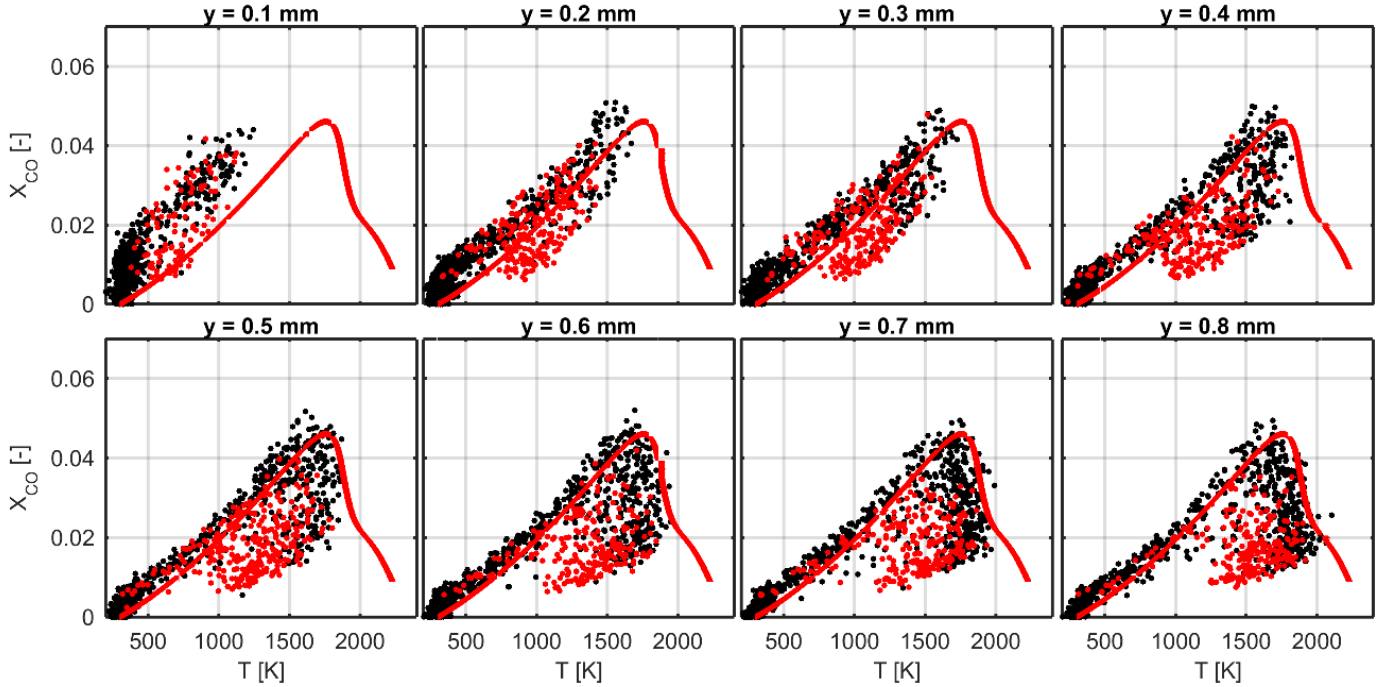
Axial height: z = 42.5 mm



- upstream instantaneous quenching point
- downstream instantaneous quenching point
- — Canterra flamelet simulation

→ Similar to laminar case but with more intermediate states

→ **CO-consumption more influenced than CO-production**

CO-consumption takes place at time-scales significantly longer than time-scales typical for heat transfer

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Conclusions – thermo-chemical states

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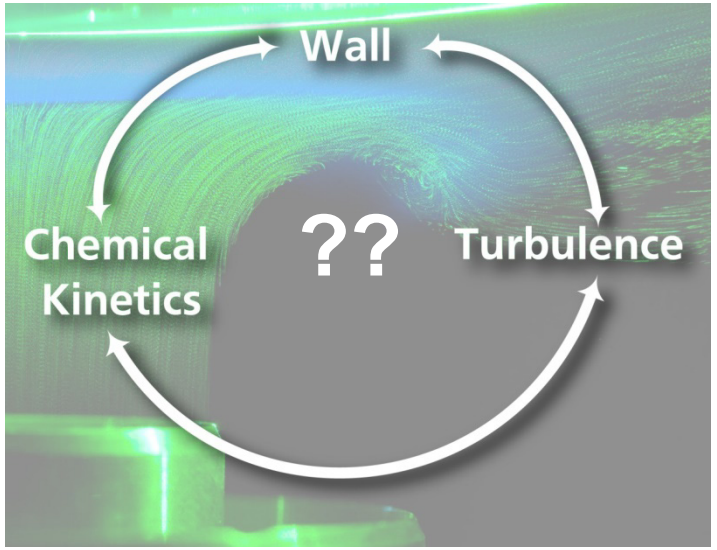
- Significant differences of CO-T-scatter plots compared to adiabatic flames
- Comparison to 2D DNS (not shown) and time-scale analysis reveals for CH_4-flames that **diffusion** rather than low temperature chemistry is **dominant**
- Quenching of flames near walls is observed at **small spatial scales**



→ Implication for combustion modeling:

- High resolution required
- Appropriate turbulence-chemistry-interaction models needed to account for heat loss in the presence of a wall

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Open issues for flame-wall interaction (1)

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- For steady and unsteady flame-wall interaction a more detailed understanding is required with regard to…
  - …Structure of velocity boundary layers
  - …Structure of thermal boundary layers
  - …Structure of concentration boundary layers
- Unsteady heat transfer and impact of turbulent heat flux
- …

Experiments
Theory
Modeling
Simulation

→ **Valid models for near-wall turbulent combustion to be developed**

- Understanding the influence of
  - Wetted surfaces (fuel or oil films)
  - Deposits

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Open issues for diagnostics needs (2)

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- Information lacking for:
  - Instantaneous structure of thermal boundary layers

  → Need for measurement of 1D-temperature profiles **→1D fs/ps CARS**

  - Unsteady heat transfer and impact of turbulent heat flux

  → Simultaneous temperature and velocity measurements near walls

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Two-beam fs/ps hybrid 1D-CARS

(A. Bohlin,C. Kliewer – CRF Sandia Livermore, USA)

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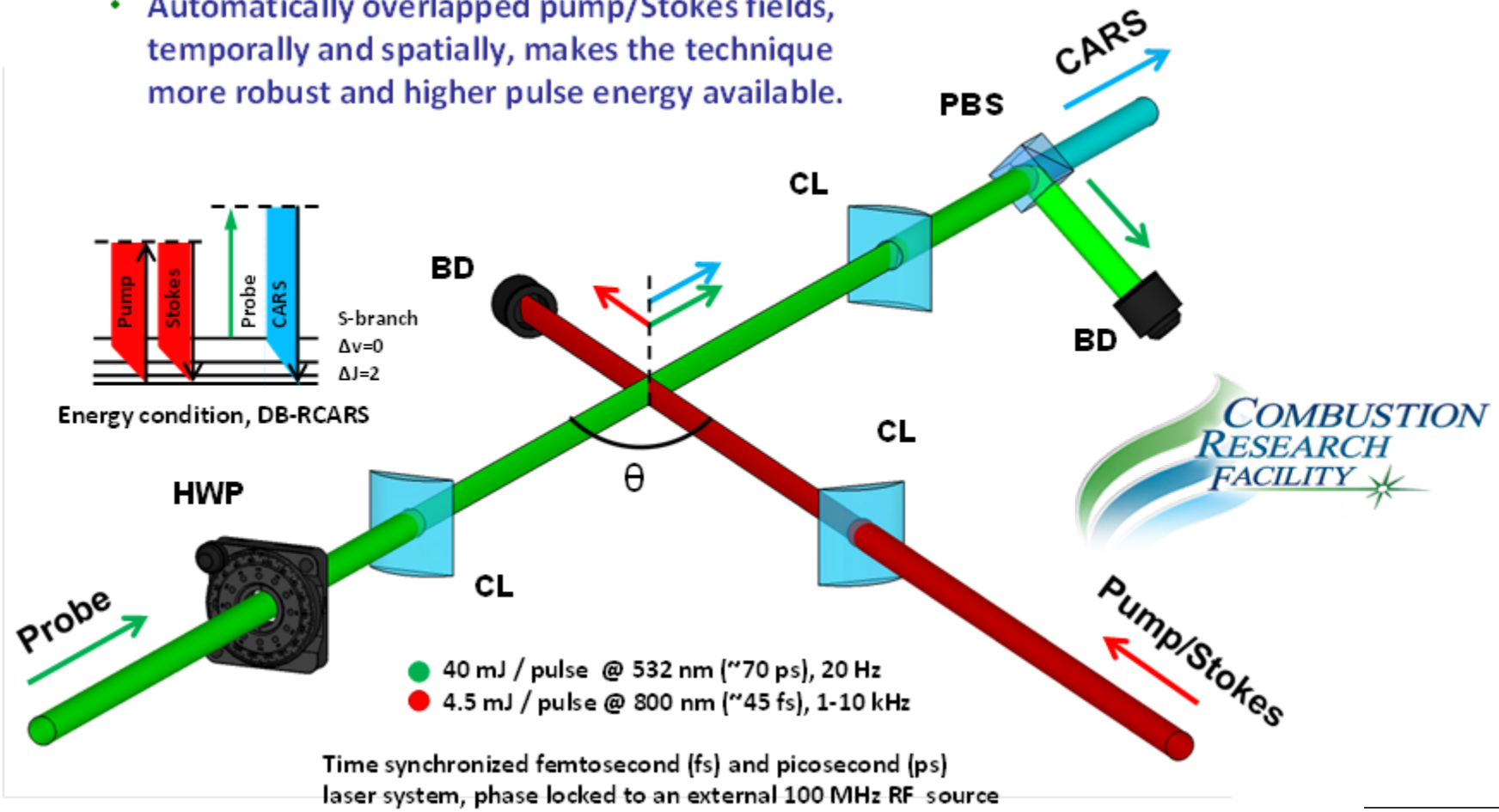
- Improved spatial resolution (< 50 µm).
- Automatically overlapped pump/Stokes fields, temporally and spatially, makes the technique more robust and higher pulse energy available.



COMBUSTION RESEARCH FACILITY

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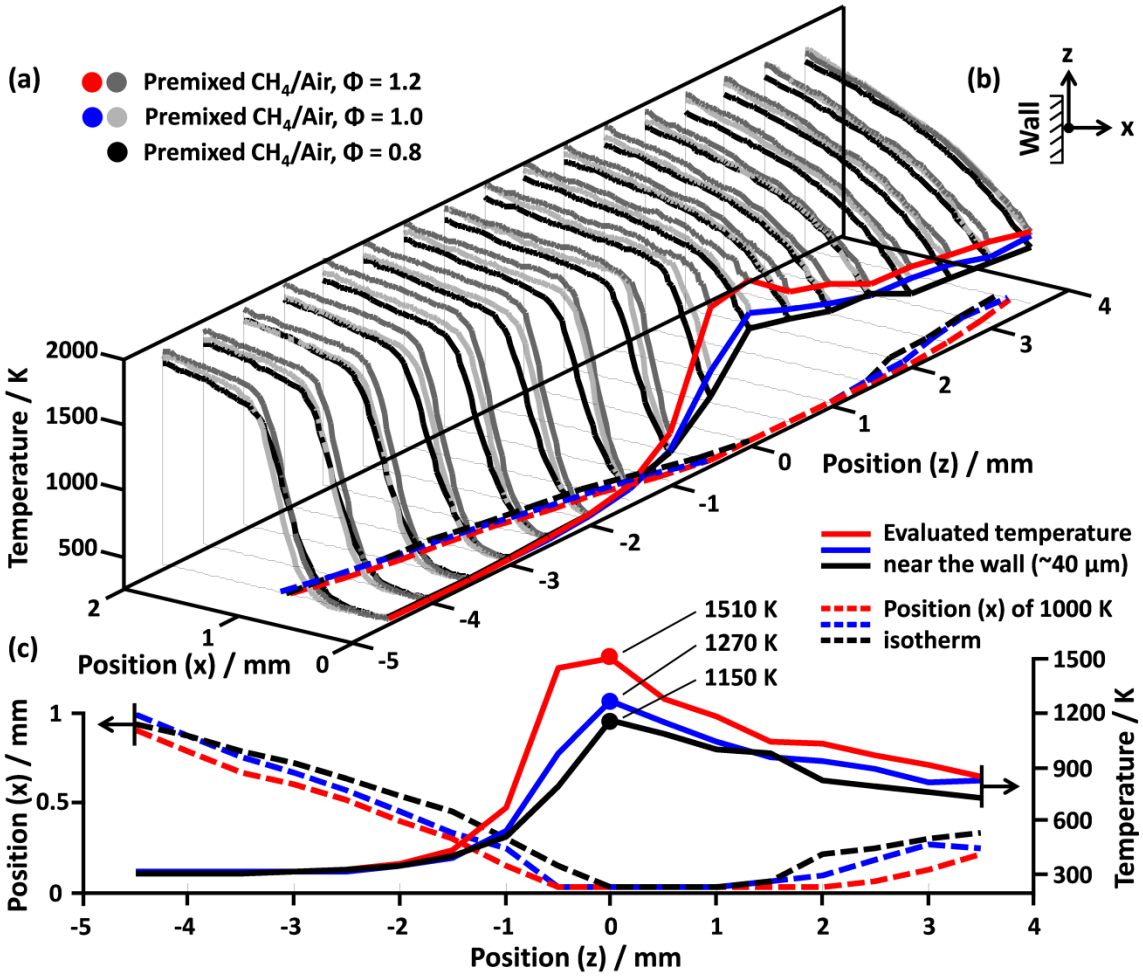
Open issues for diagnostics needs (3)

- 1D-CARS-thermometry
- Cooperation with CRF-Sandia
- C. Kliewer, A. Bohlin, C. Jainski A. Dreizler
- Bohlin et al. PCI 36, 2017