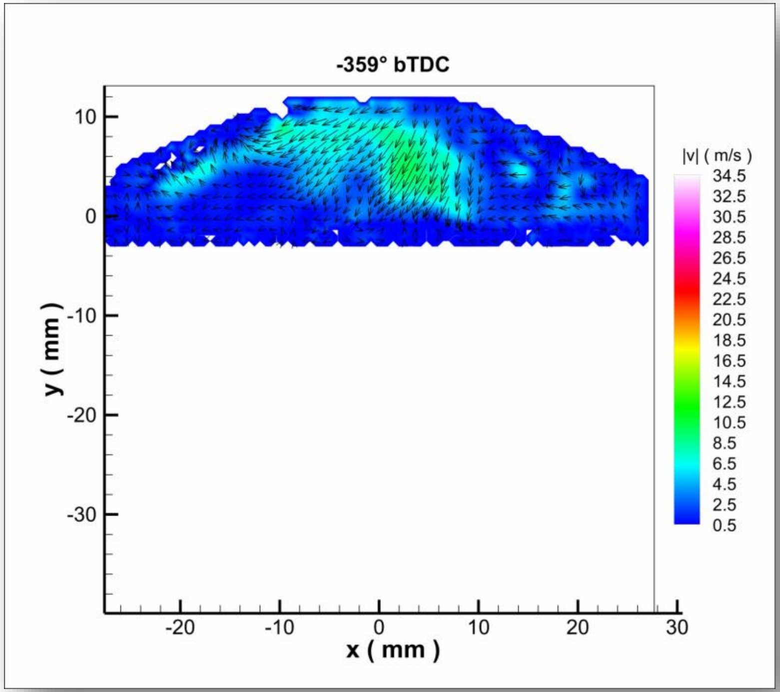
Chapter 8:
Towards 4D-imaging

TU Darmstadt, Germany
Mechanical Engineering – Reactive Flows and Diagnostics

A. Dreizler



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

Contents

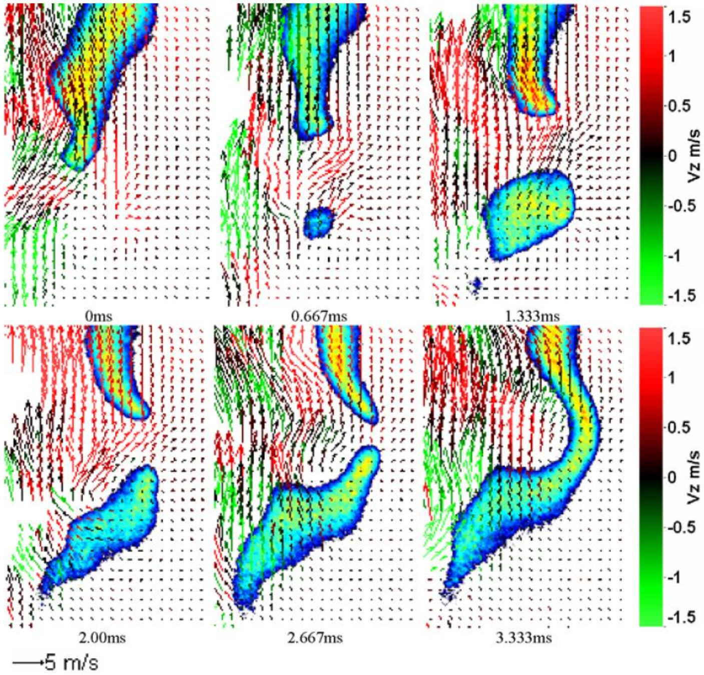
Motivation for 4D-imaging

- 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??

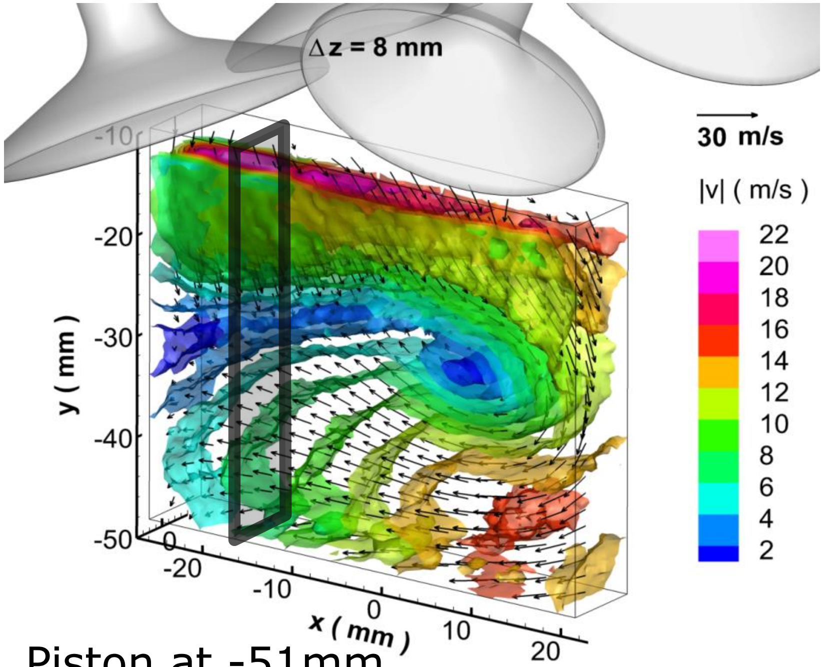
PCI 32, 2009, Gordon et int. Dreizler



Towards 4D-diagnostics – previous work

- 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

270° bTDC

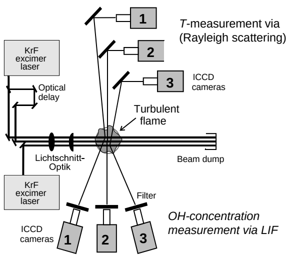


Tomo PIV in IC engine
PCI34, 2013, Baum et int. Dreizler

Piston at -51mm

Towards 4D-diagnostics – previous work

- 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.)



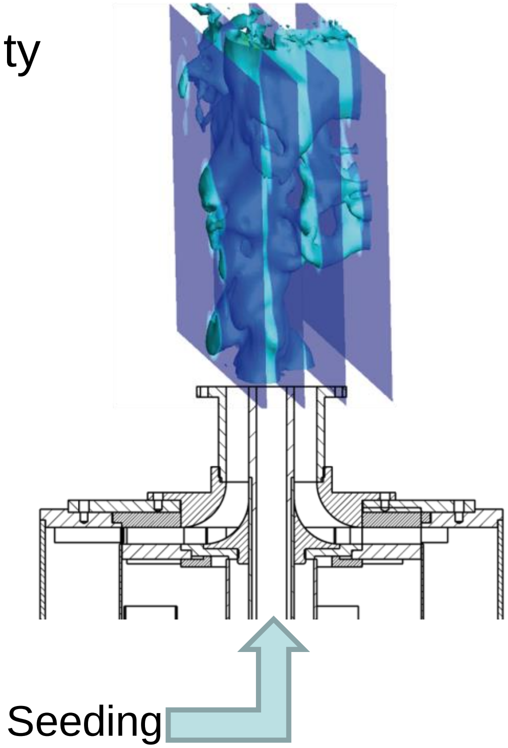
  - Method 3: tomographic reconstruction using absorption/emission spectroscopy, needs many projections (observation directions)

    → limited data tomography (Muruganadam et al., Wagner&Dreizler et al. and many others)

Quasi-4D-diagnostics – flow visualization

- 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)



Experimental setup

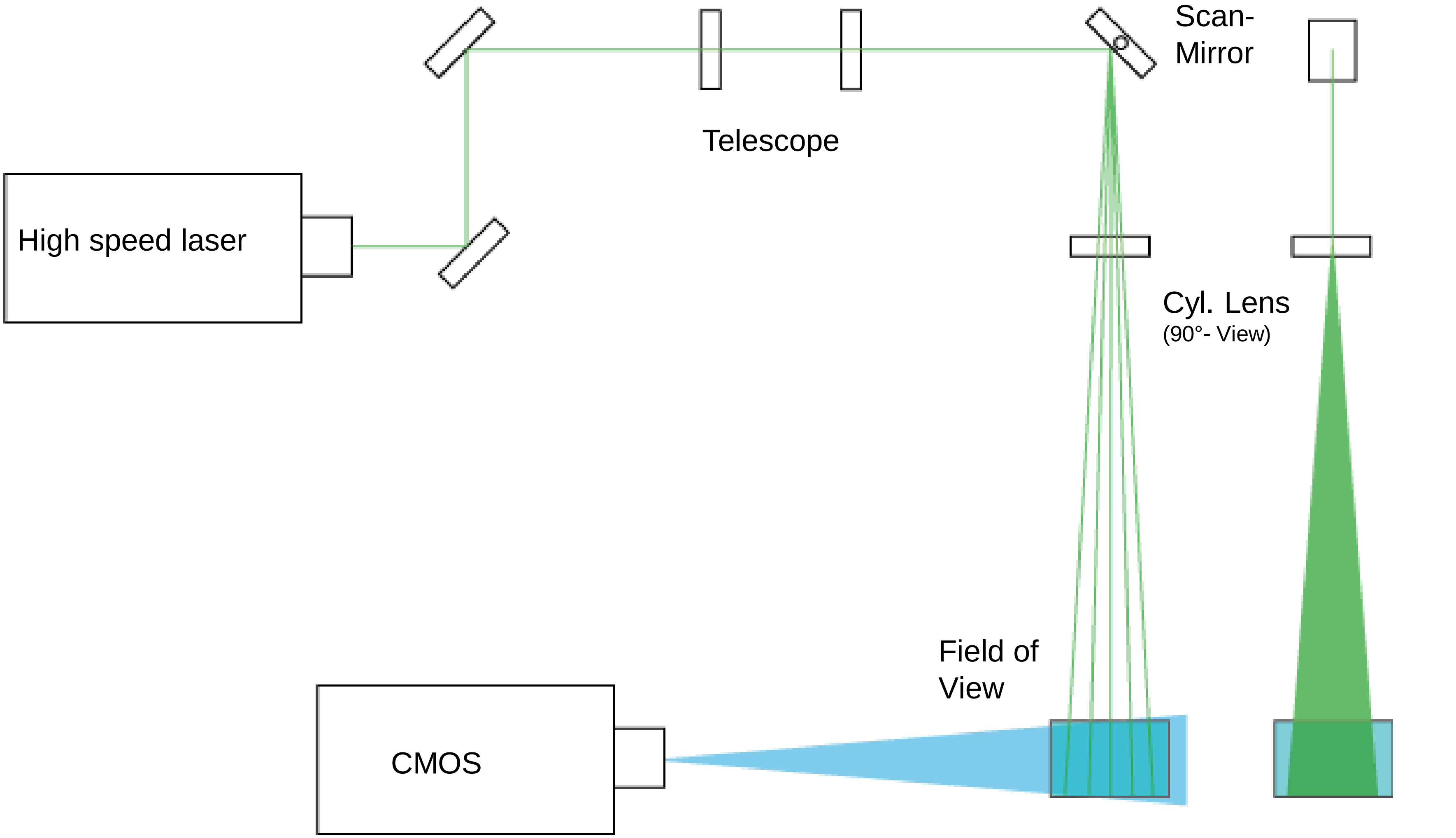
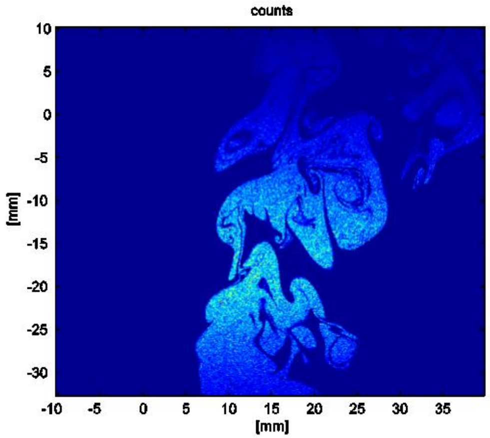
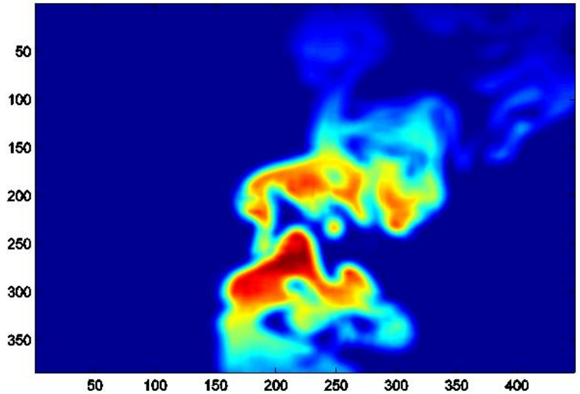


Image post-processing

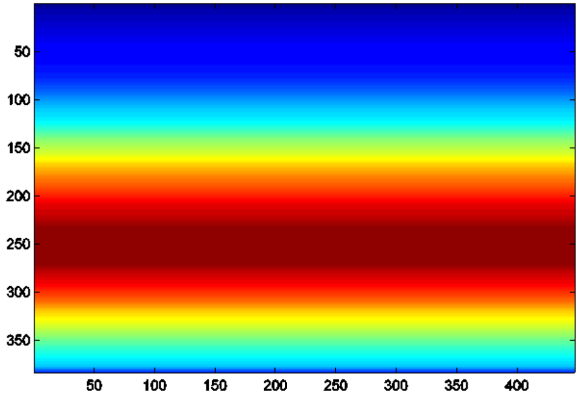


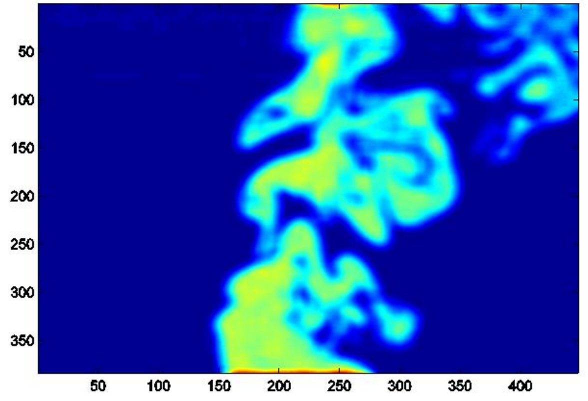
Original Image

Gauß-, Medianfilter



Laser Beam Profile

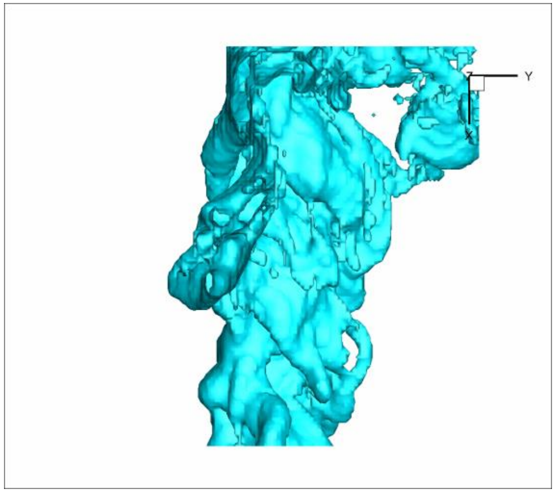




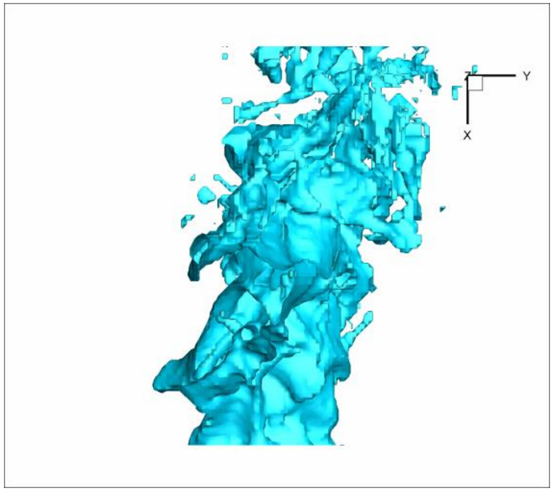
Results for low Reynolds numbers

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

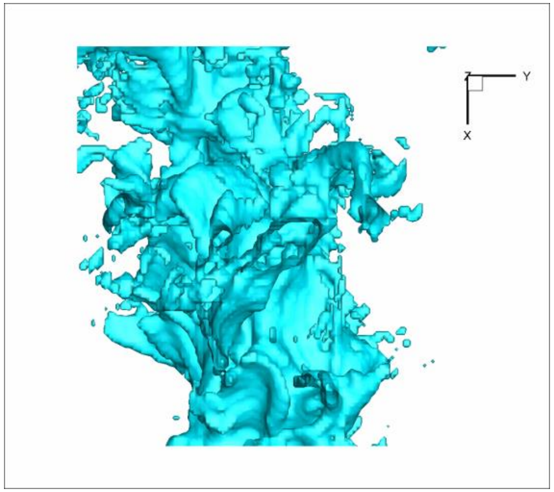
Field of view ~ **50x50x50**mm
Jet: 3800 l/h Re ~ 1000
Annulus: 800 l/h Re ~ 800



0% Swirl (S_{geo} = 0)



50% Swirl (S_{geo} ≈ 1)



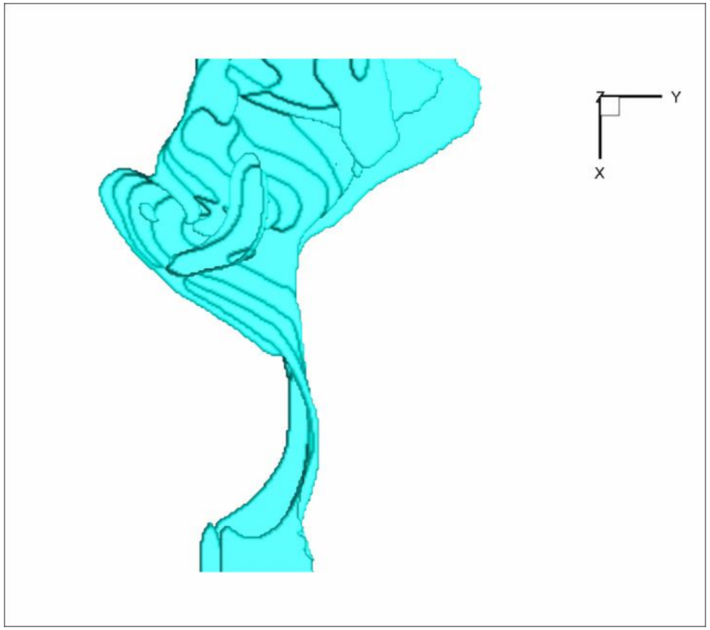
100% Swirl (S_{geo} ≈ 2)

⇒ Increasing swirl breaks up core flow faster

Results for intermediate Reynolds numbers

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

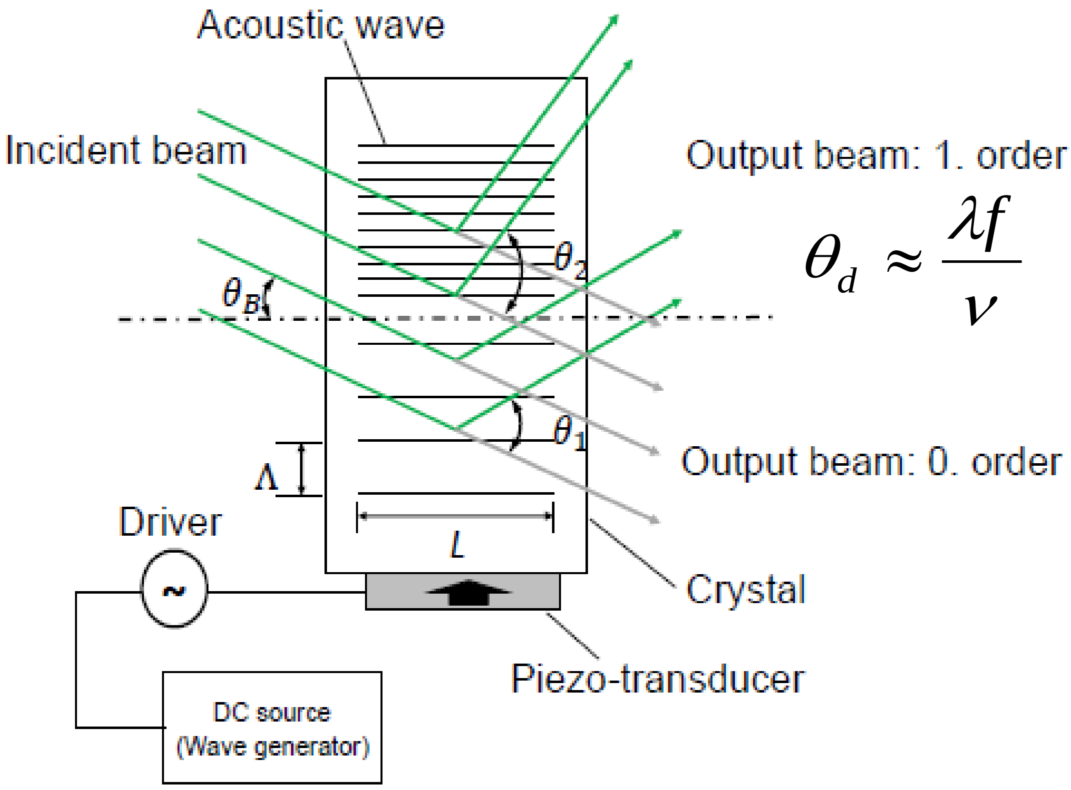
→ **Need for higher scanning rates**

⇨ Spatial resolution too low due to „low“ repetition rate
Better reconstruction algorithms required

Most recent development: Acousto-optic deflector

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

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

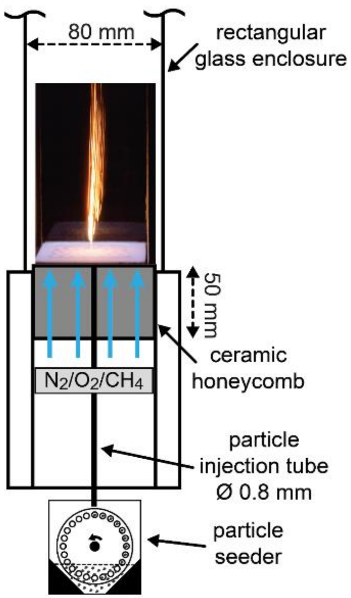


$$\theta_d \approx \frac{\lambda f}{v}$$

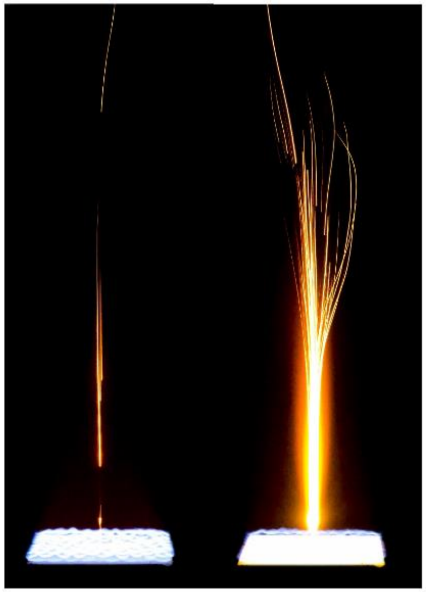
T. Li et al. Appl. Phys. B 2017

Application to coal combustion

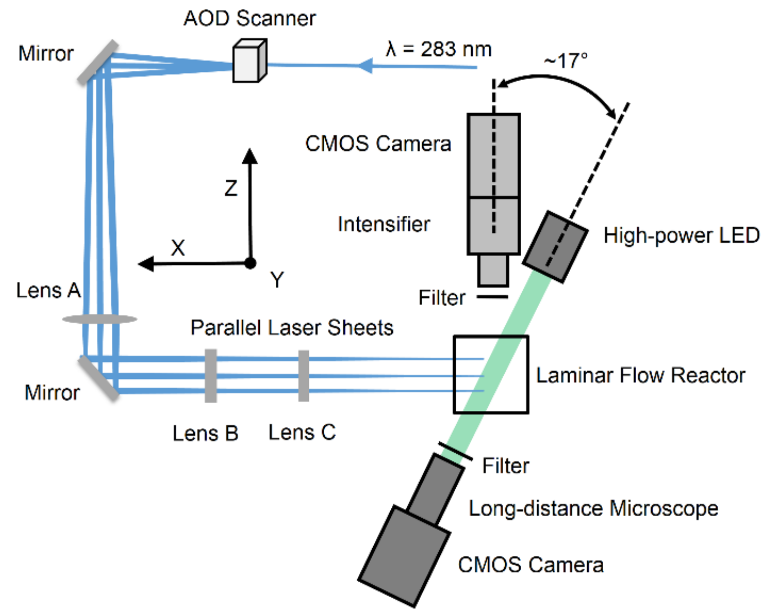
- Single particle and particle cloud reactor



(a)


Single Particle
Particle Cloud
(b)

- Scanning OH-PLIF



(b)

- Volume: $18 \times 18 \times 4$ mm^3
- In-plane and out-of-plane spatial resolution:100 µm and 400 µm
- Temporal resolution: 1 ms (reconstruction from 10 planes recorded at 10 kHz

T. Li et al., SDEWE 2019

Quasi 3D OH LIF: volatile combustion around single particle

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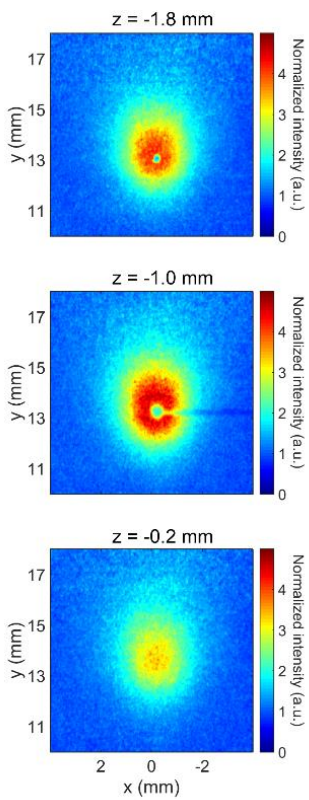
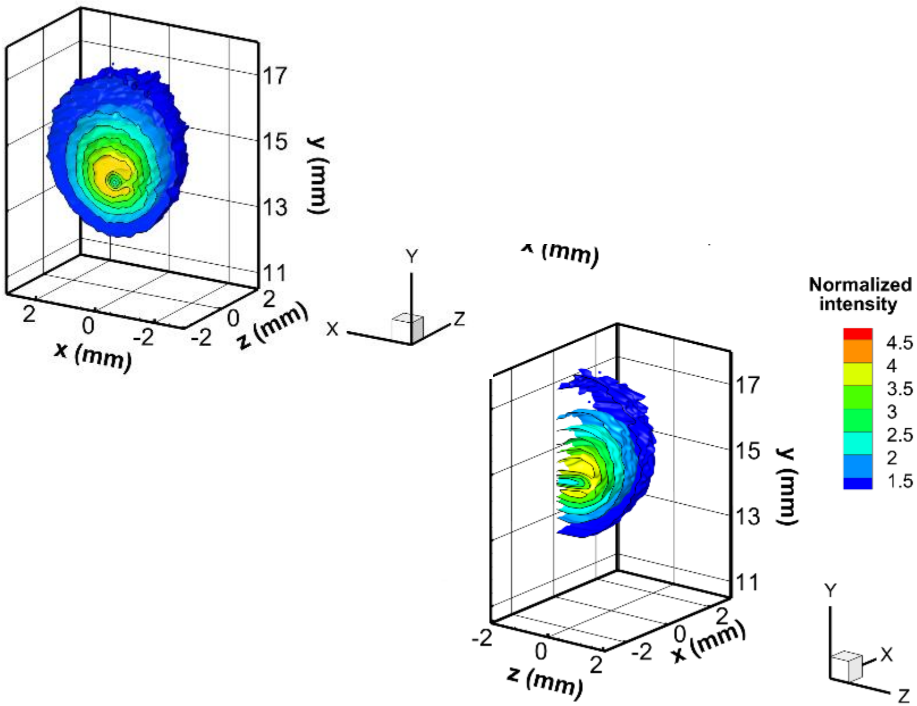
- Pre-processed OH-LIF images of volatile combustion of single particle at three laser sheet positions.



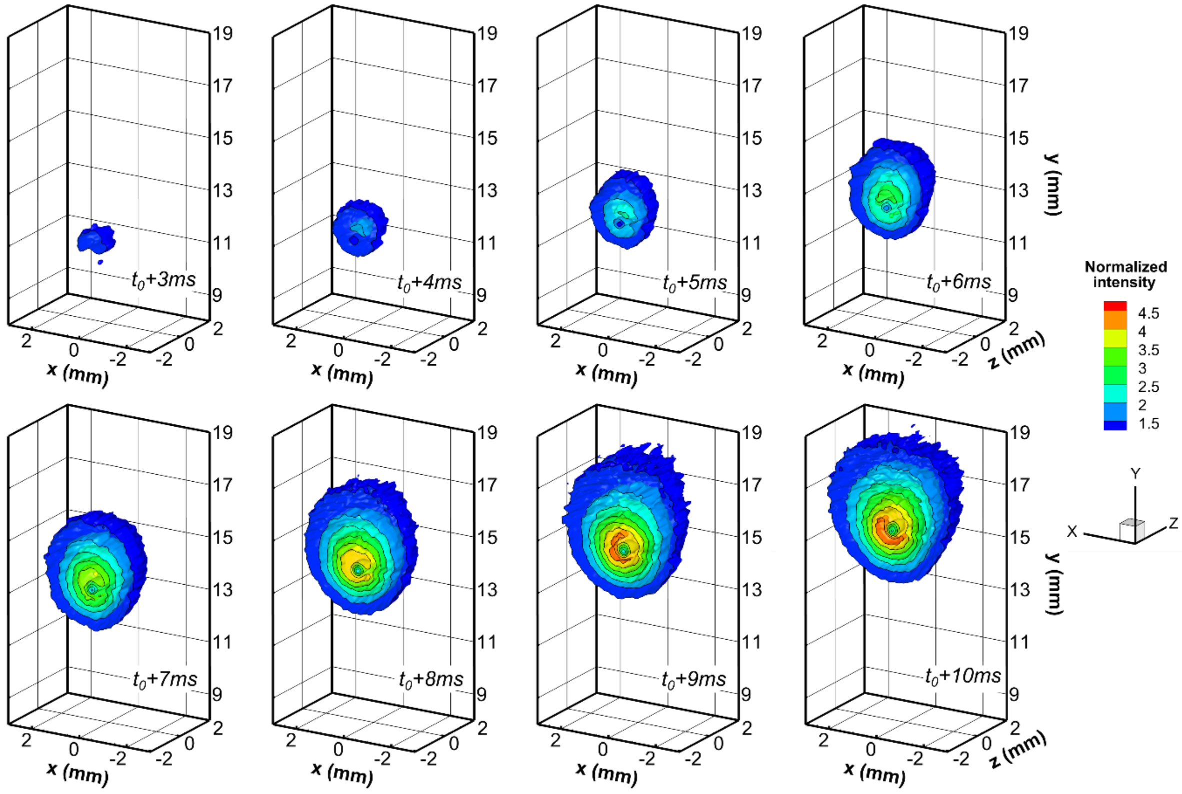
- Reconstruction of OH signals displayed with intensity iso-contours and slices with two different viewing angles



T. Li et al., SDEWE 2019

Quasi 3D OH LIF: volatile combustion around single particle

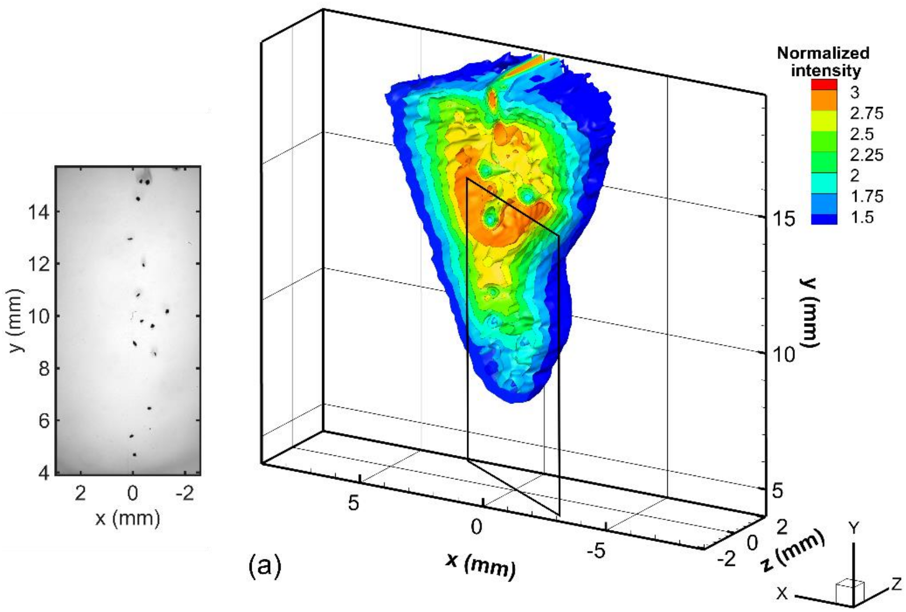
- Temporal sequence of the reconstructed volumetric OH signal of an individual coal particle during volatile combustion
- Onset of ignition is denoted as t_0, sequence of 7 ms



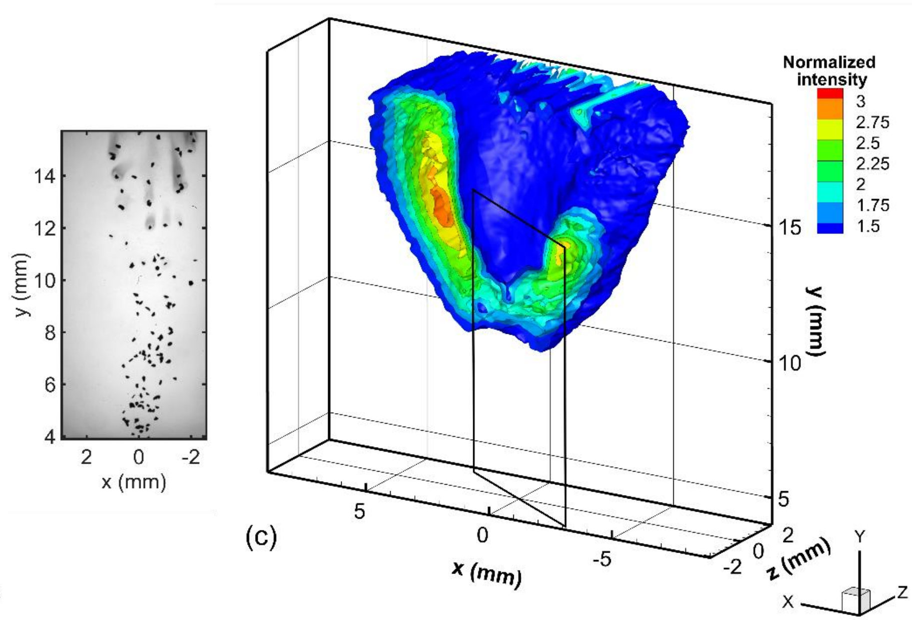
T. Li et al., SDEWE 2019

Quasi 3D OH LIF: volatile combustion around single particle

- Snapshot comparison of volatile flame topology for two different particle densities
- Simultaneous line-of-sight backlight images (left) with FOV highlighted by the rectangle in the 3D flame reconstruction (right)



Single-particle combustion mode



Particle-cloud combustion mode

T. Li et al., SDEWE 2019

Dual plane imaging

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.

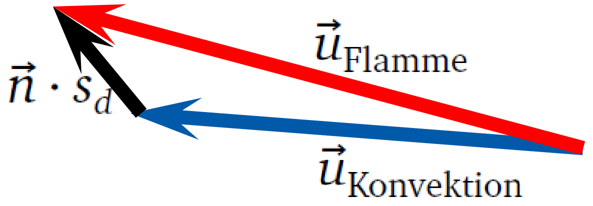
Premixed flame propagation – background

- 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

- 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

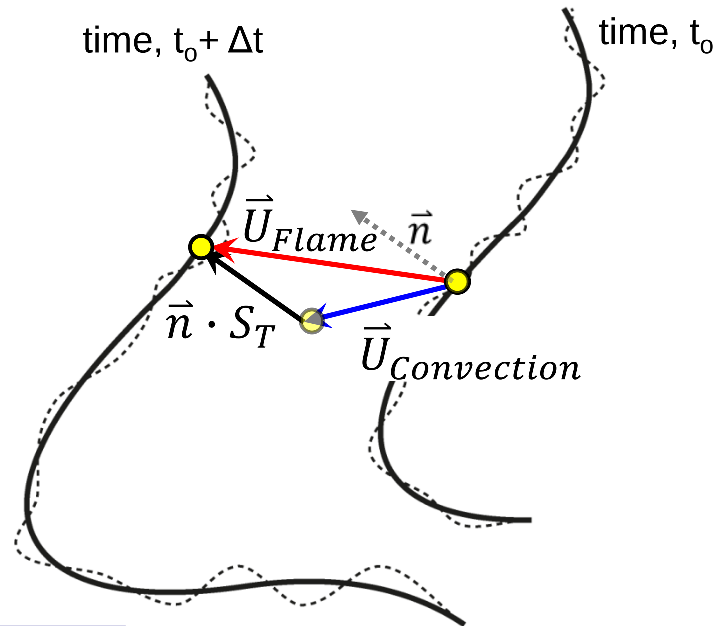
- How to resolve quantities?
  - $\vec{n}$
  - $\vec{U}_{Flame}$
  - $\vec{U}_{Convection}$

$\vec{n}$, $\vec{U}_{Flame}$ → 3D flame front tracking

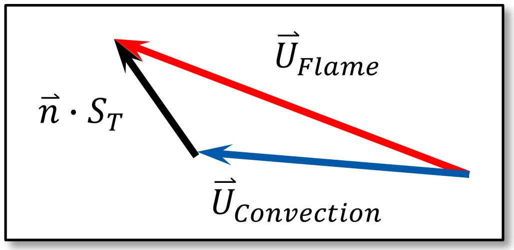
$\vec{U}_{Convection}$ → Measure *u,v,w* velocity components

3D flame front tracking + Measure *u,v,w* velocity components → Extract S_T

Vectorial Schematic (projected in 2D)



Turbulent flame speed during early flame dev.



Volumetric flame front tracking:

OH-PLIF in two parallel planes

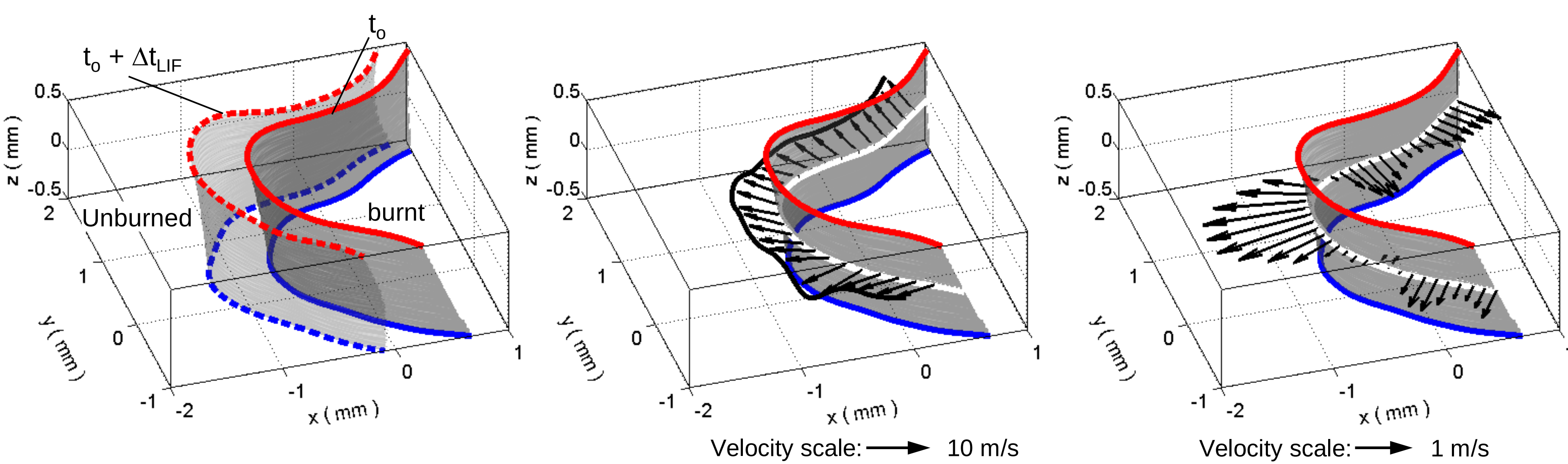
Stereo PIV:

Sandwiched between OH-PLIF planes at high rep. rates

Flame Surfaces:
Reconstructed from 2 planes

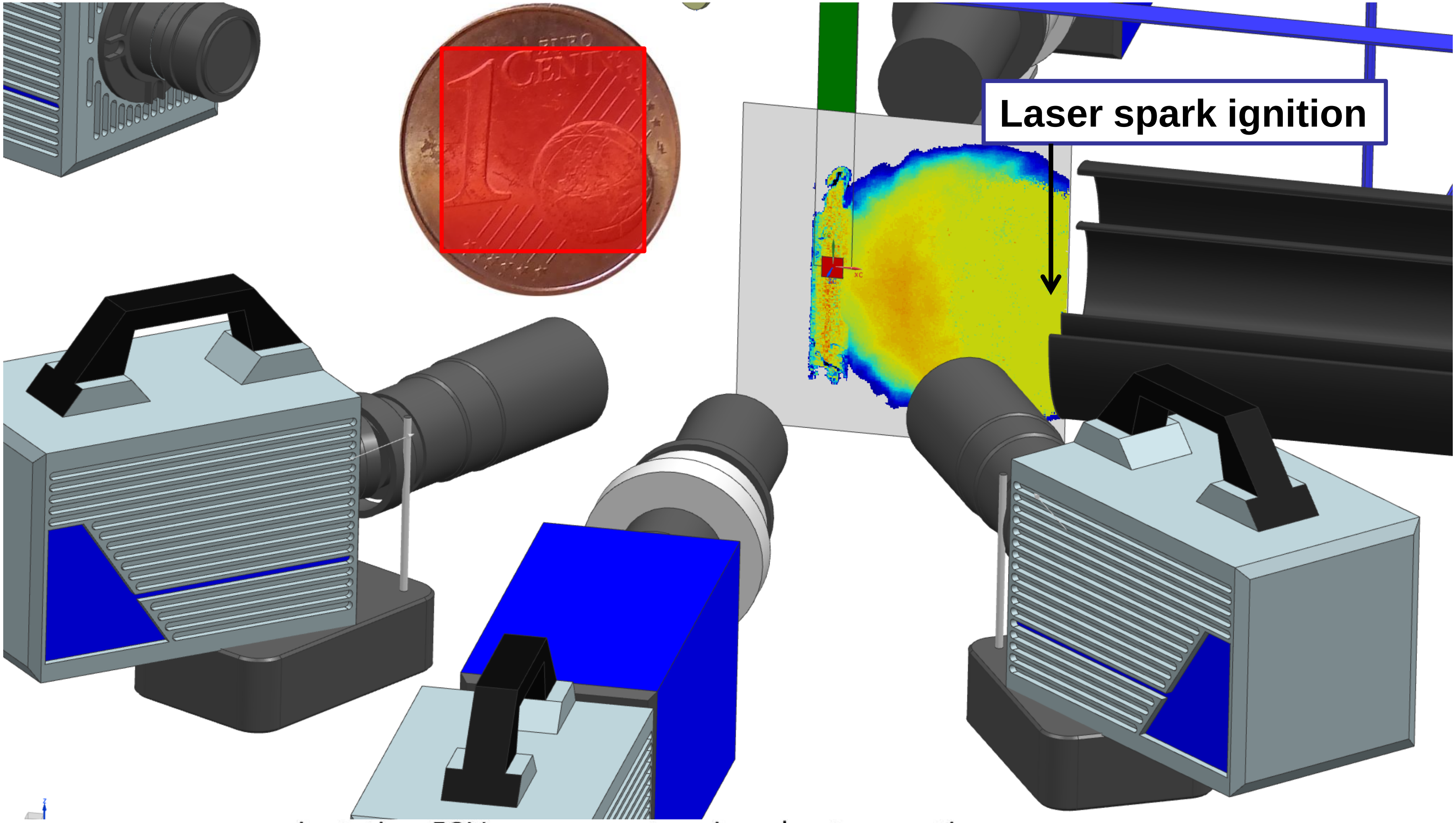
Conv. vel. 0.4 mm from surface

Flame speed in normal direction



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

Premixed flame propagation – exp. setup

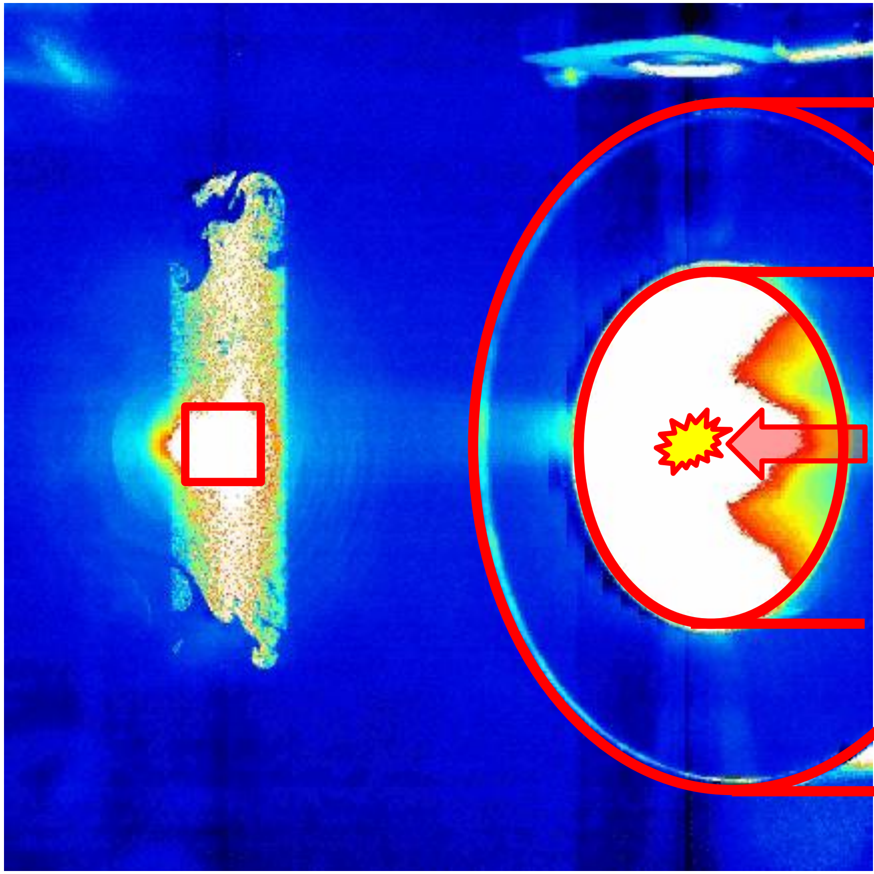


orientation FOV   top view sheet separation

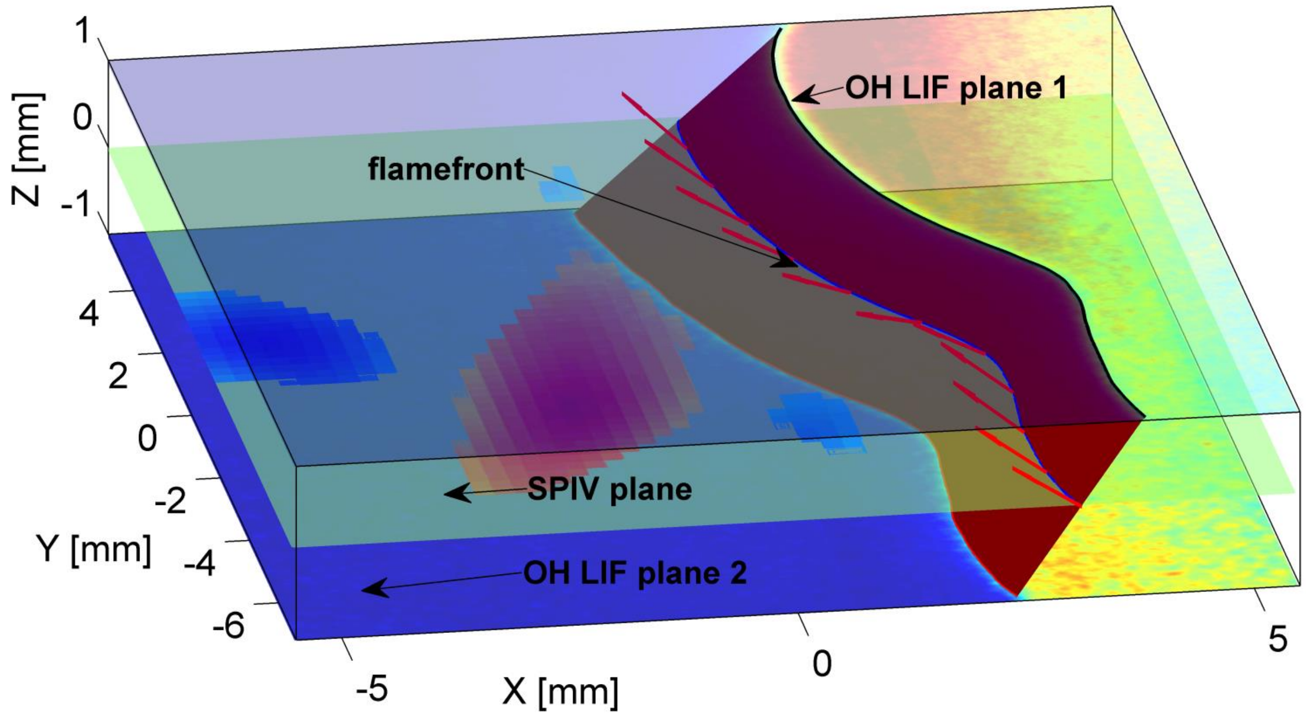
Method – *Configuration*

- **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



Visualization of flame surface in 3D space



+ information on temporal development → displacement speed

Temporal sequence of flame sequence

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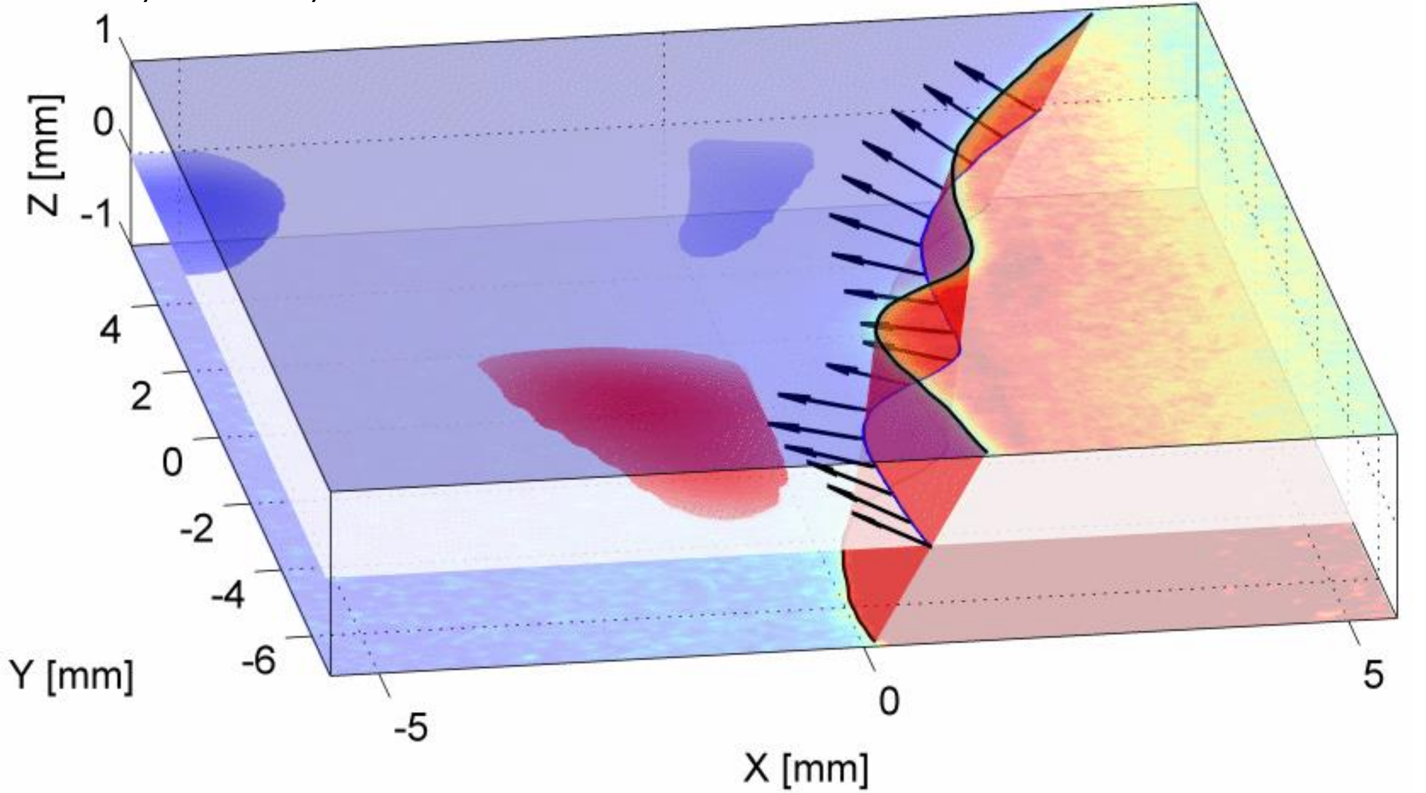
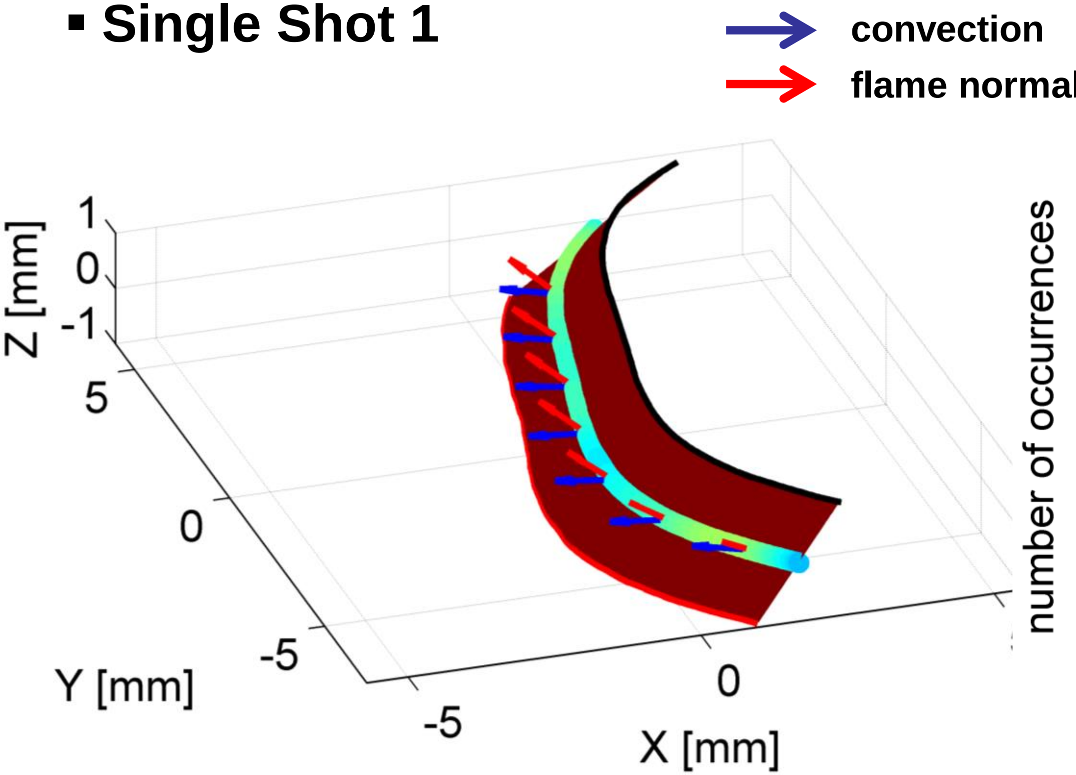
CH_4/air, Φ=1.0, Re=10,000

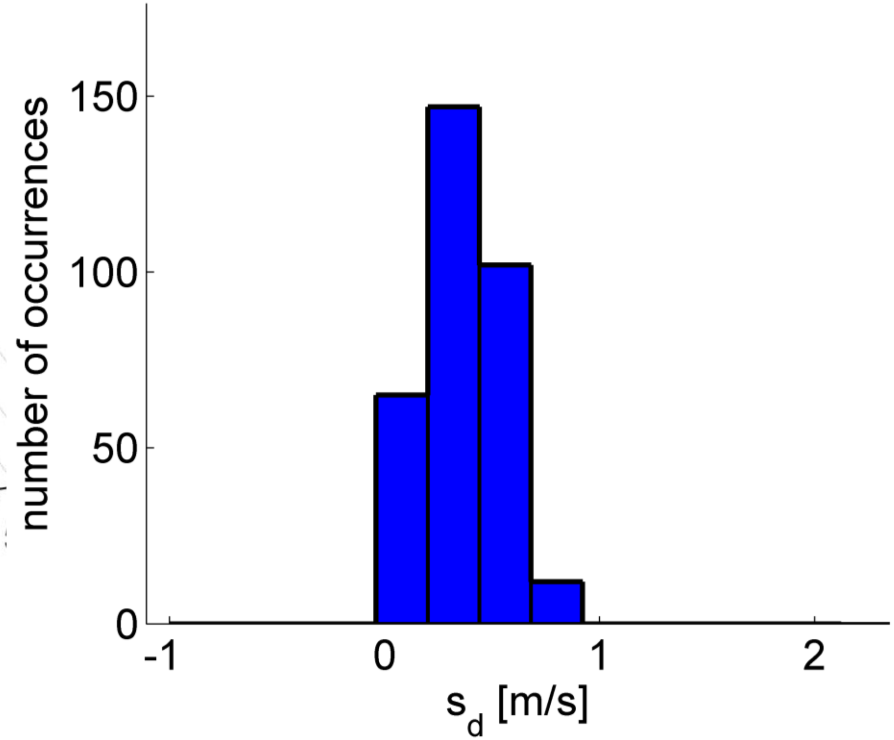


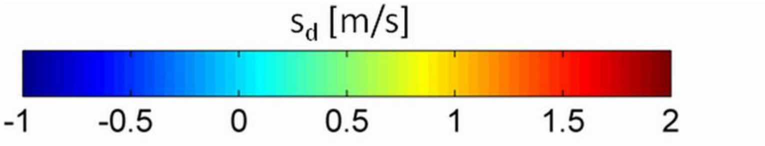
RSM Reaktive Strömungen + Messtechnik

Single Shots

- **Single Shot 1**

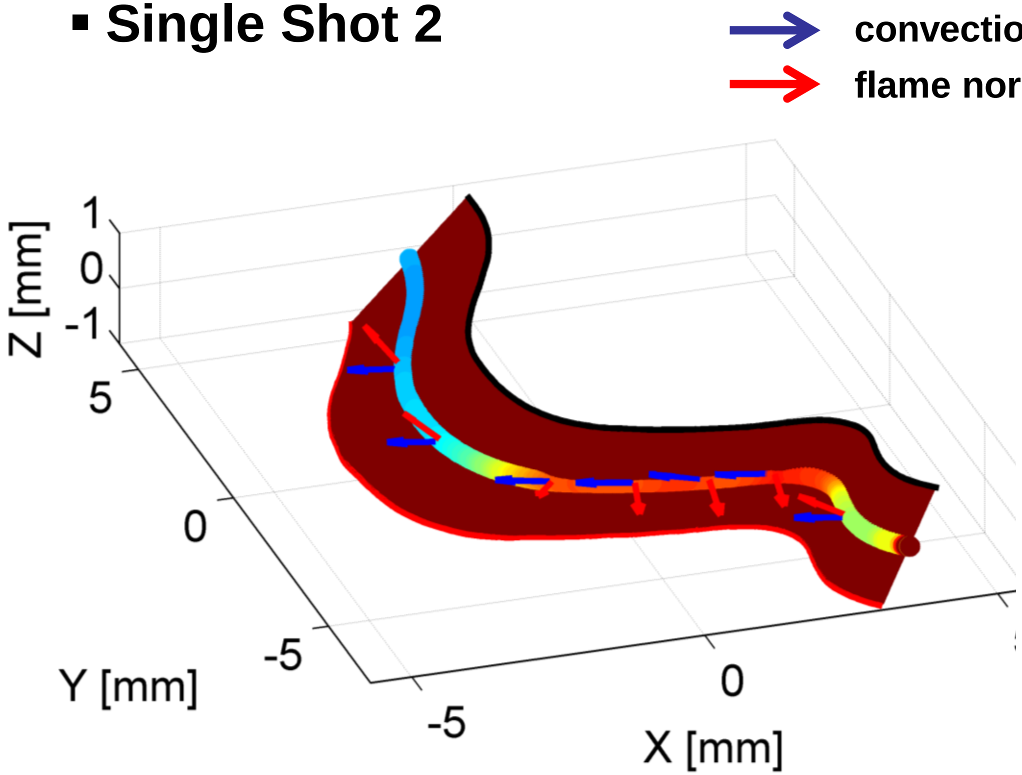


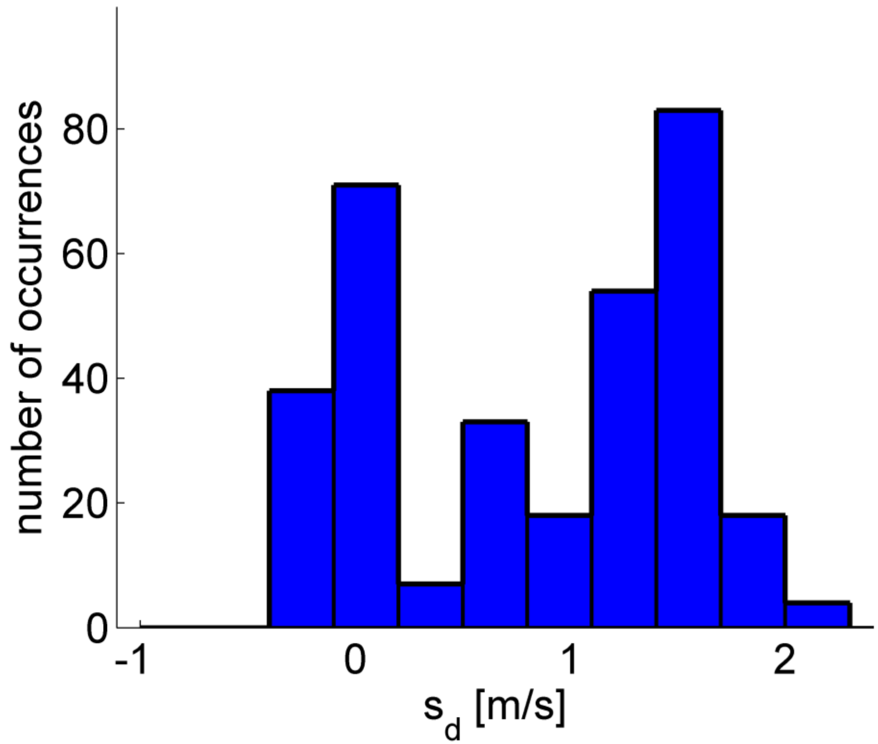


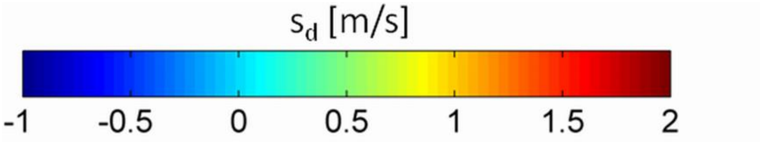


Single Shots

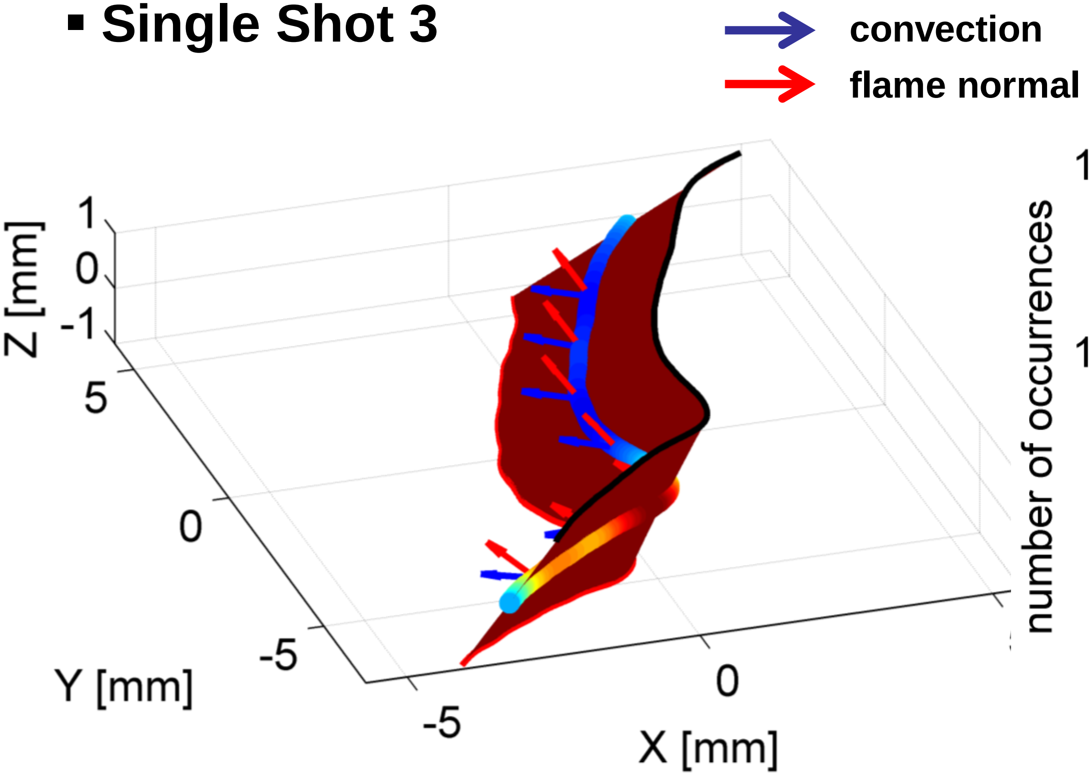
- **Single Shot 2**

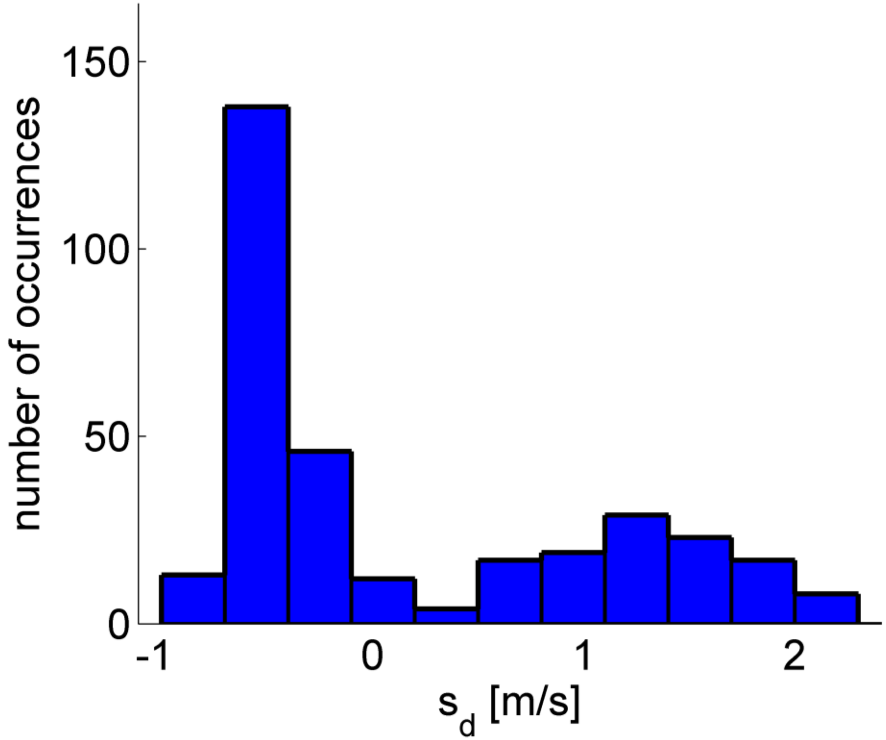


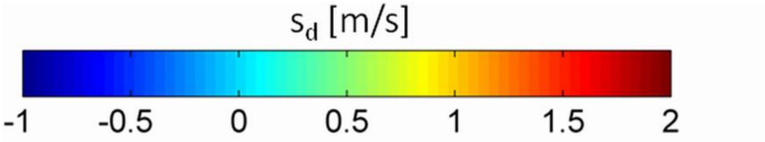




- **Single Shot 3**







Displacement speed statistics

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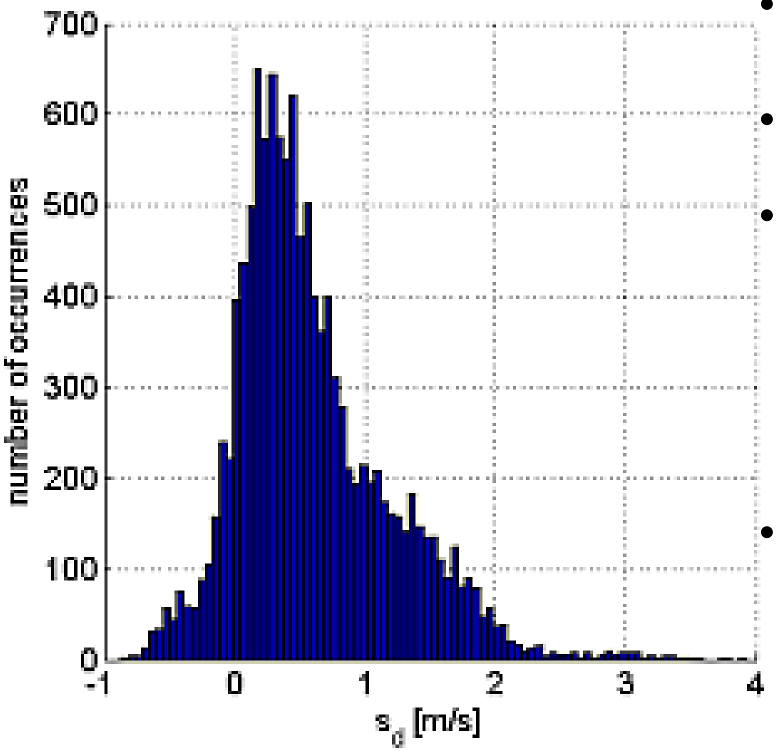
- **Displacement speed statistics (CH_4/air; ϕ = 1.0)**



- 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:

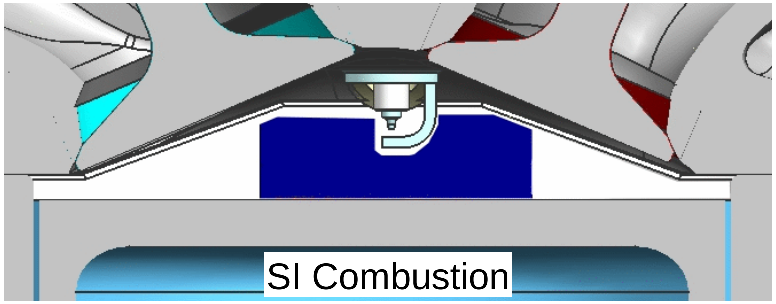
  ➢ Gran & Chen 1996

  ➢ Bilger & Kim 2005

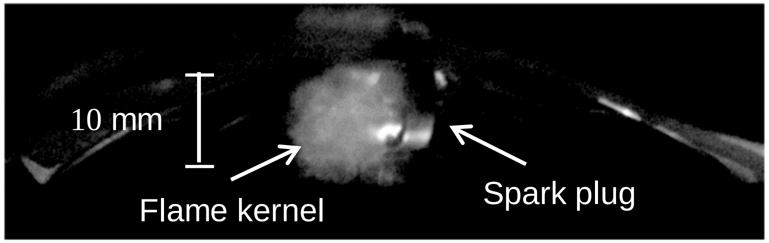
RSM Reaktive Strömungen + Messtechnik

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

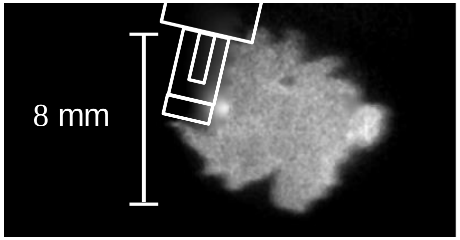
- Early flame development, less than 5% burned mass
- Issue here:
  1. Influence of turbulence on local **flame displacement speed**
  2. Cyclic variations



Mie scattering, evaporating oil drops



Chemiluminescence imaging

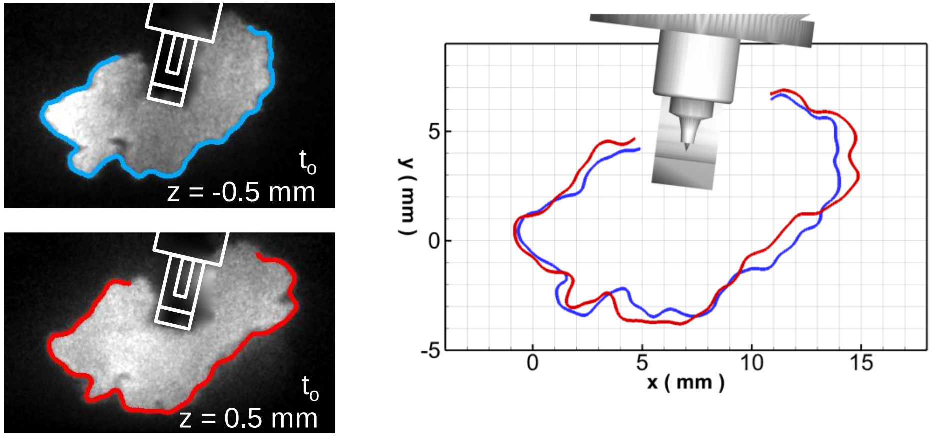


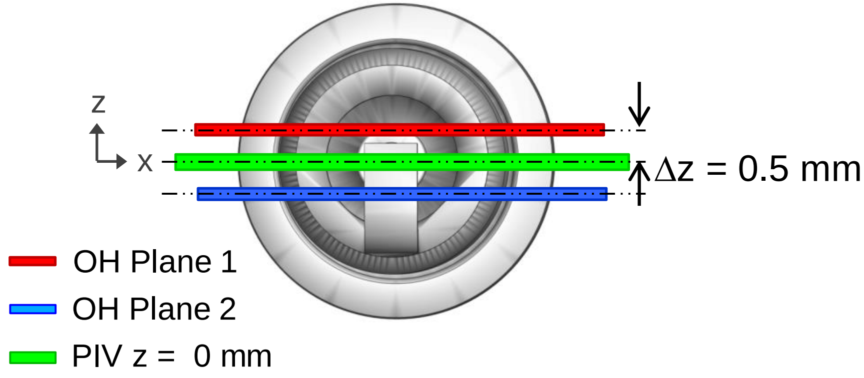
OH-LIF imaging

Experimental setup

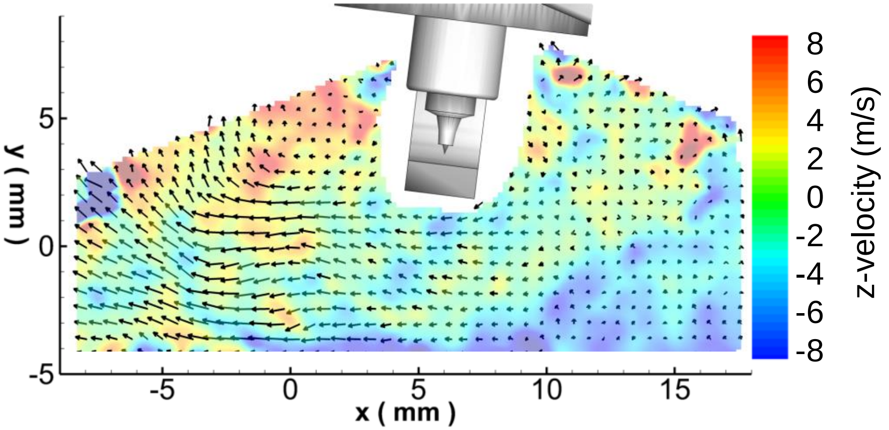
- Dual-plane OH-LIF
  - Two independent UV laser systems (double-pulsed)
  - OH LIF images in parallel planes
- SPIV
  - Central tumble plane

Dual-plane OH-LIF





Stereoscopic PIV

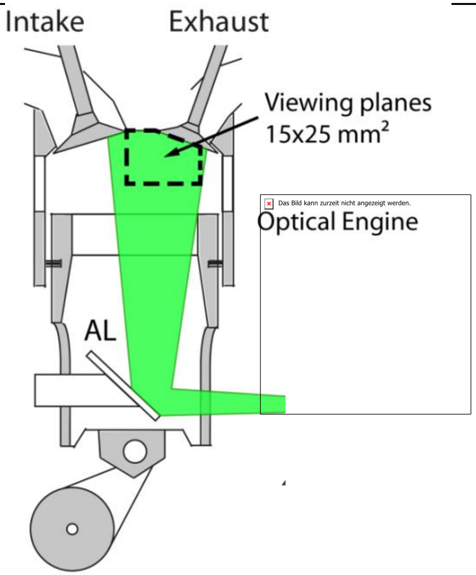


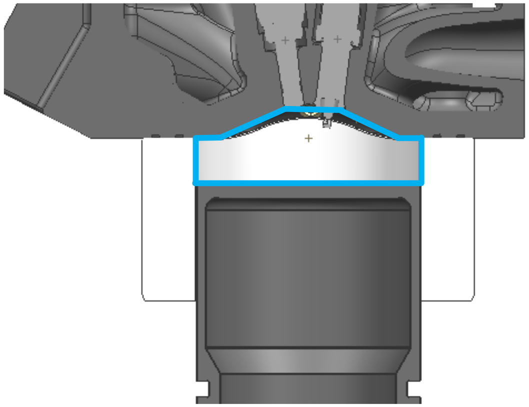
Operating conditions

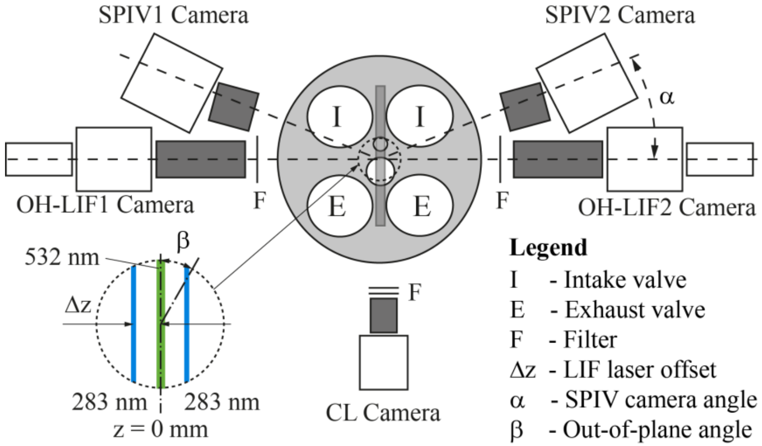
- 800 RPM
- Iso-octane, air, $\lambda = 1$
  - Port-fuel, homogeneous
- Intake: P = 0.95 bar, T = 295 K
- Spark 19º bTDC

- HS-PIV, Chemiluminescence
- 4 shot OH-LIF (2 shots each plane, $\Delta t = 50\mu s$) @ 14°bTDC

- Spray-guided cylinder head

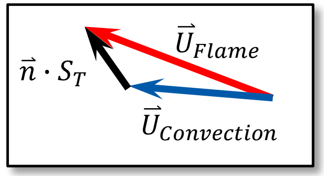


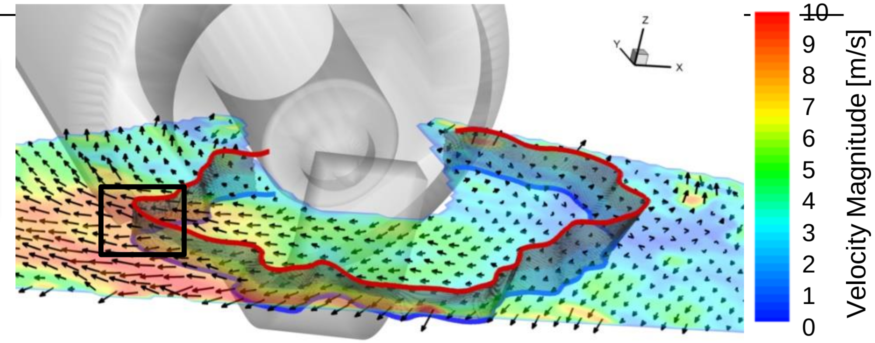




Turbulent flame speed during early flame dev.

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

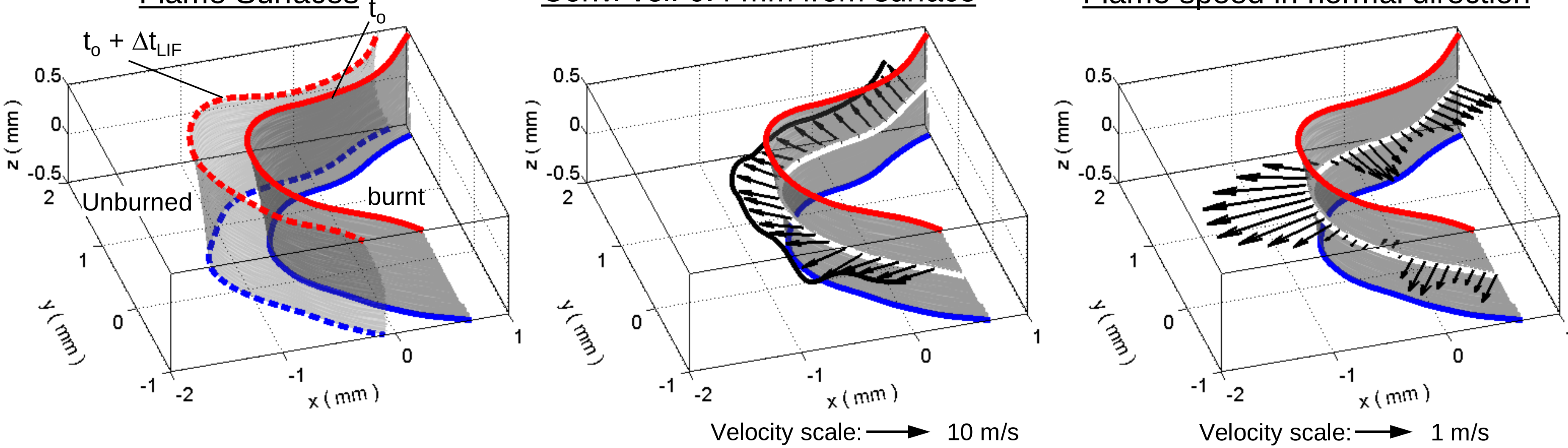




Flame Surfaces

Conv. vel. 0.4 mm from surface

Flame speed in normal direction

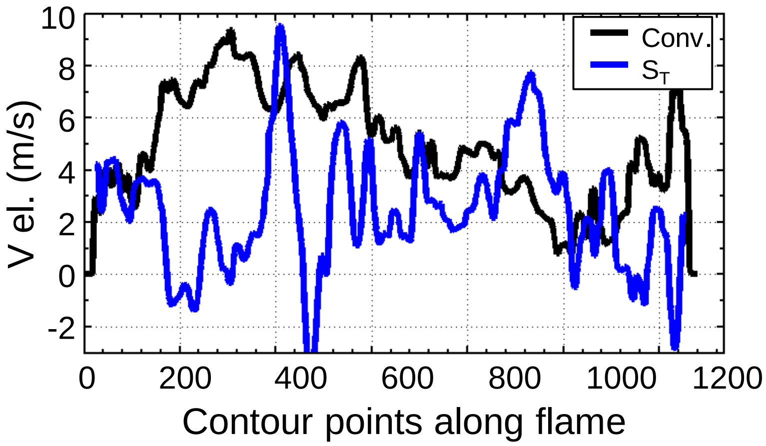


- Large range of convection velocities
  - 7 – 10 m/s
- Turbulent flame speed
  - -1.0 – 2.5 m/s

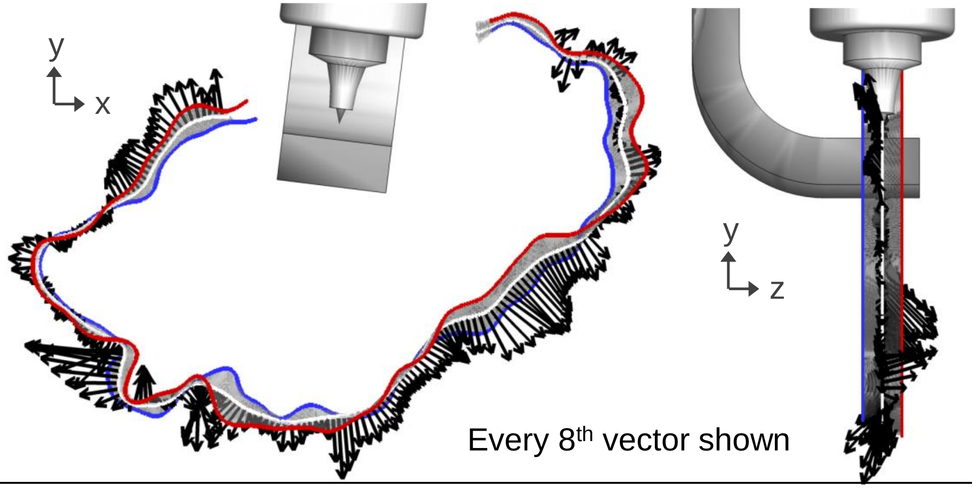
Turbulent flame speed during early flame dev.

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

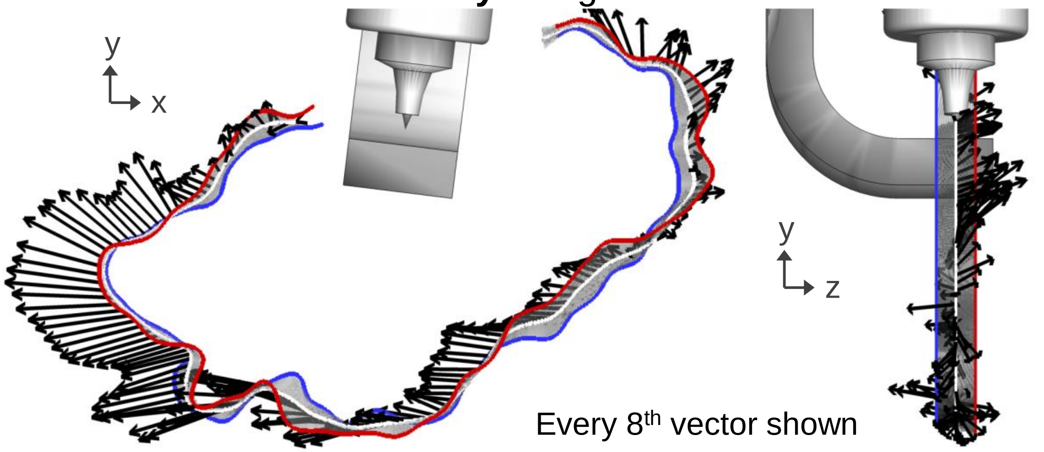
Velocity Scale: → 8 m/s



Flame speed (S_T) along flame surface



Convection Velocity along flame surface



Flame displacement speed during early flame development

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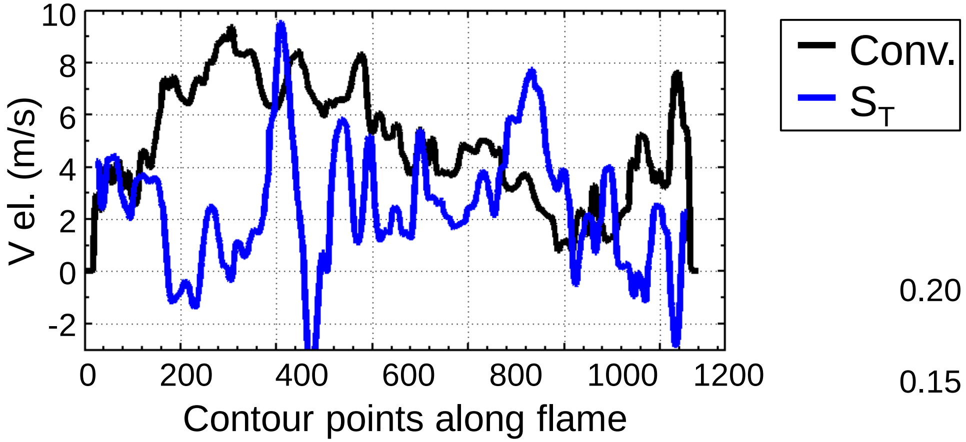
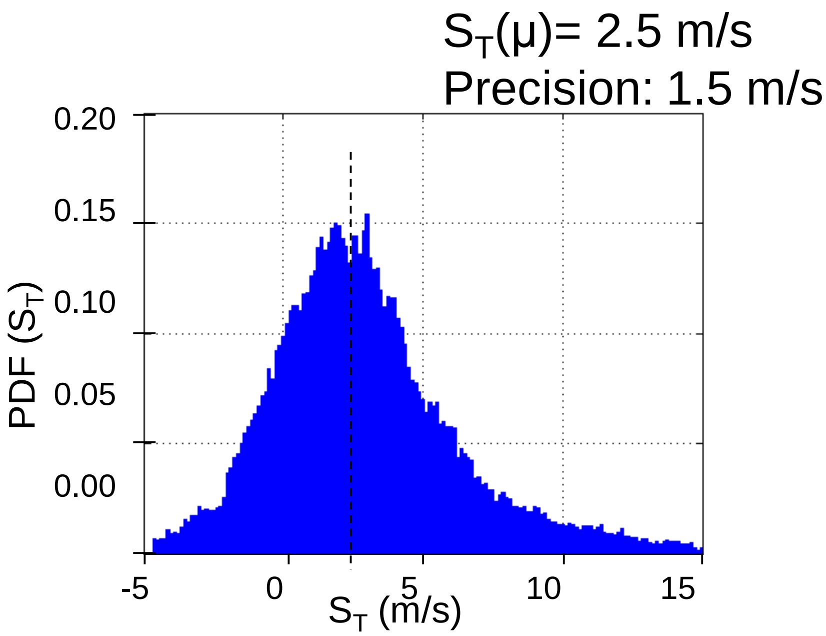
- Statistical Quantities
  - Distribution of S_T (80 cycles)

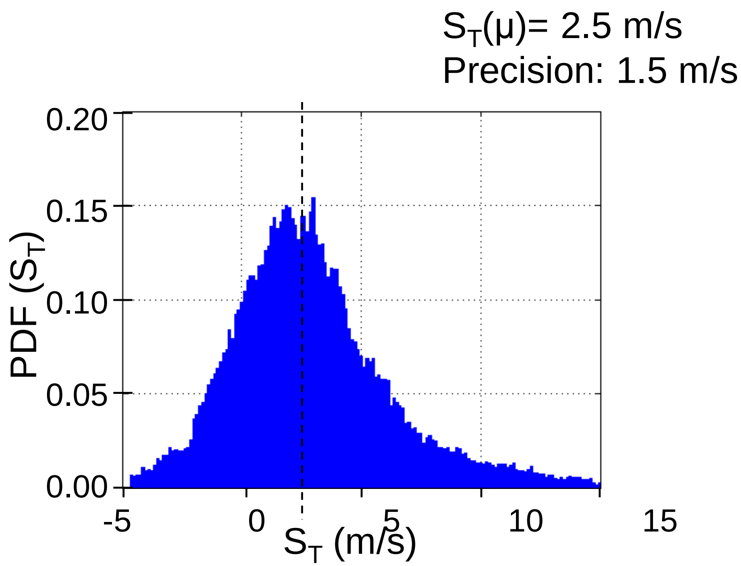




RSM Reaktive Strömungen + Messtechnik

Statistics of turbulent flame speed

- 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)

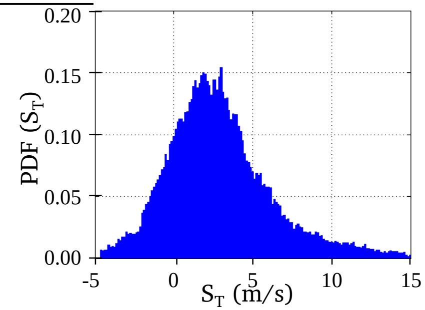


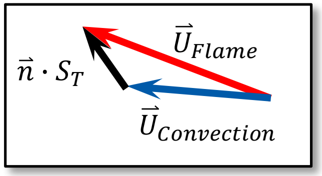
- Strong flame wrinkling due to
  - High turbulence levels
  - Thermal-diffusive /hydrodynamic instabilities (promoted by thin flames at high pressure)

Info instabilities

Negative end of the PDF

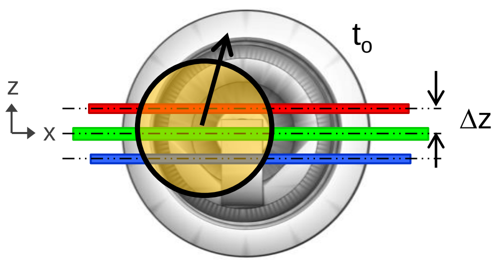
- Negative flame speeds
  - Flame displacement relative to flow
    - Not rate of consumption!





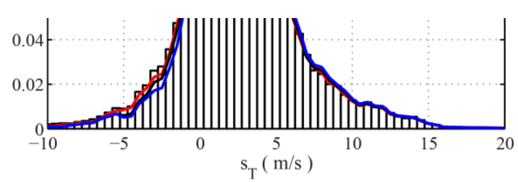
Planar imaging

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



Precision

- LIF Resolution: 0.08 mm
  - $\Delta S_T = 1.5$ 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

- 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

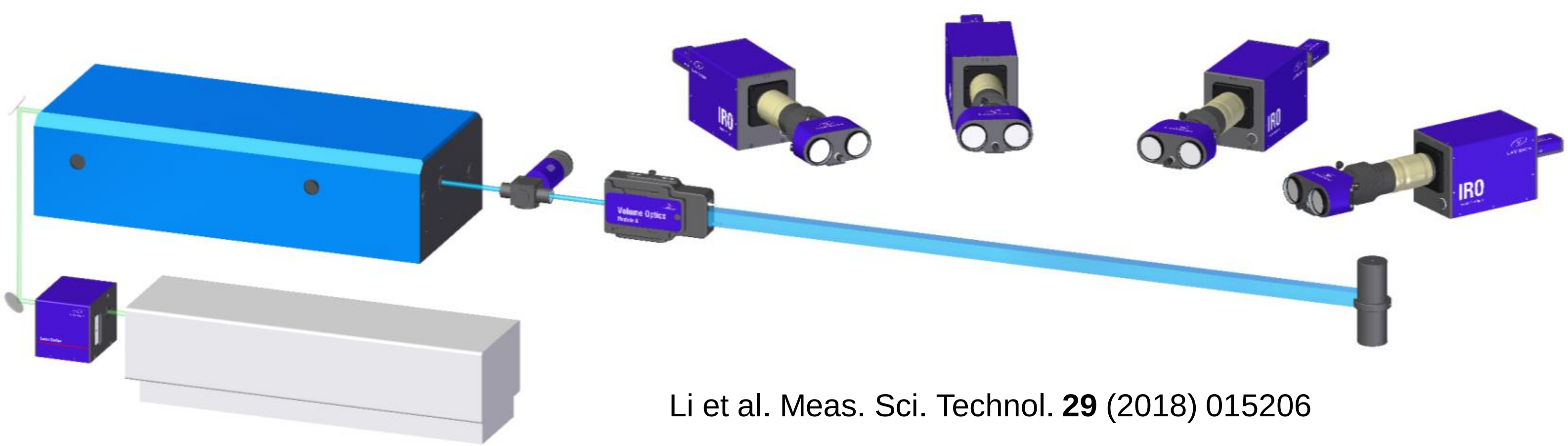
Setup Tomo LIF

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 $A^2\Sigma \leftarrow X^2\Pi$ (v'=1, v"=0) band of hydroxyl radicals
- 20 mJ at probe volume of **3x3x3 cm^3**



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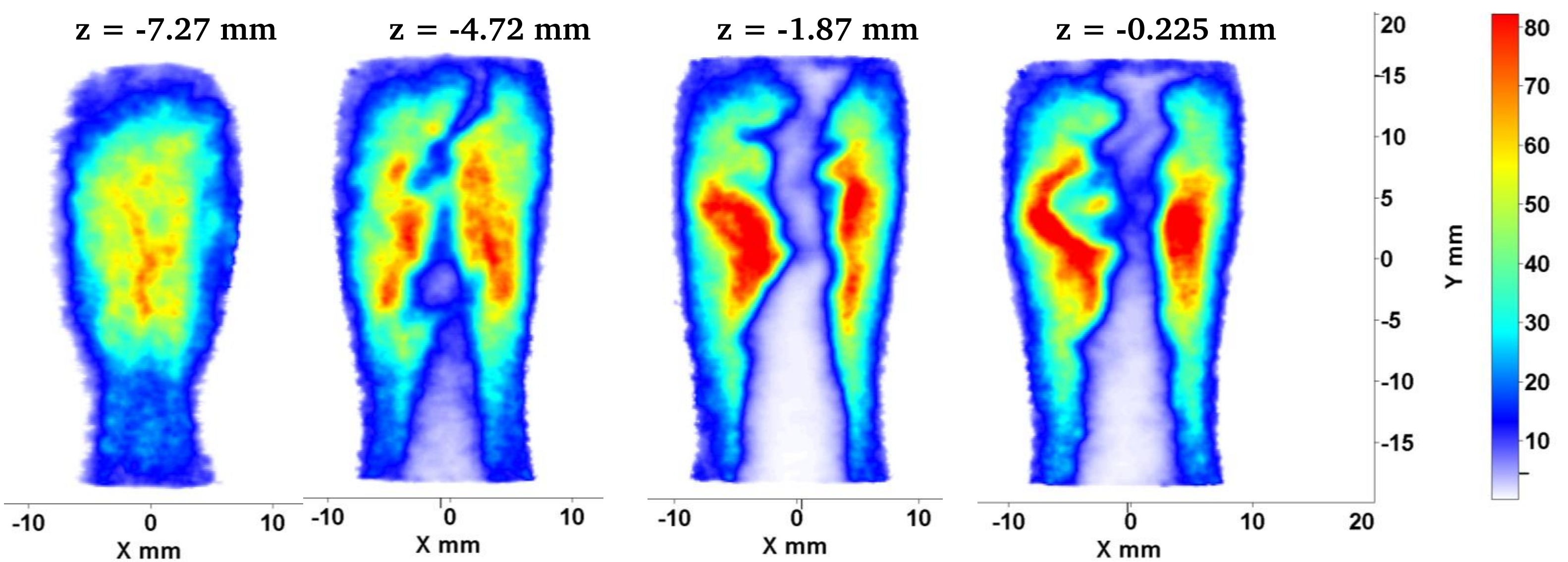
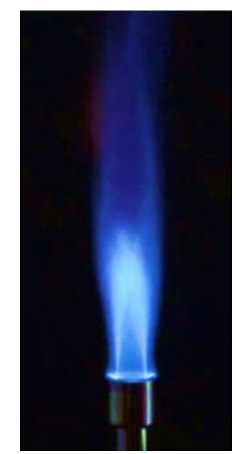
Tomographic reconstruction
Example turbulent Bunsen flame

- 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

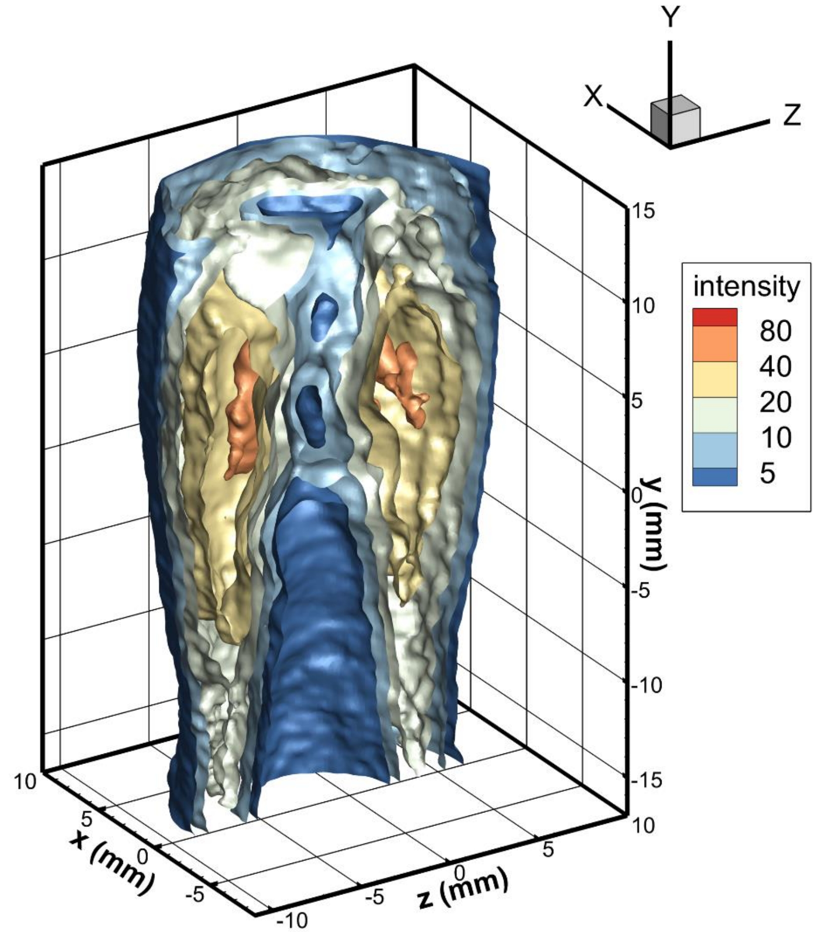
Reconstructed z-planes of turbulent Bunsen flame





Tomographic reconstruction
Example turbulent Bunsen flame

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



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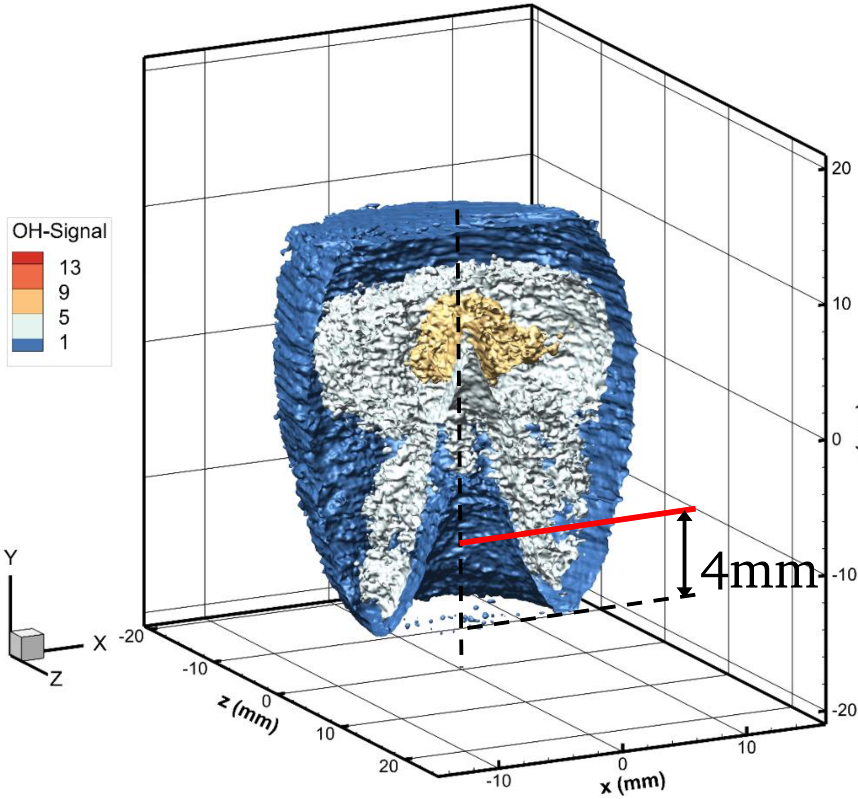
Comparison with 2D PLIF measurements
Laminar Bunsen flame

- 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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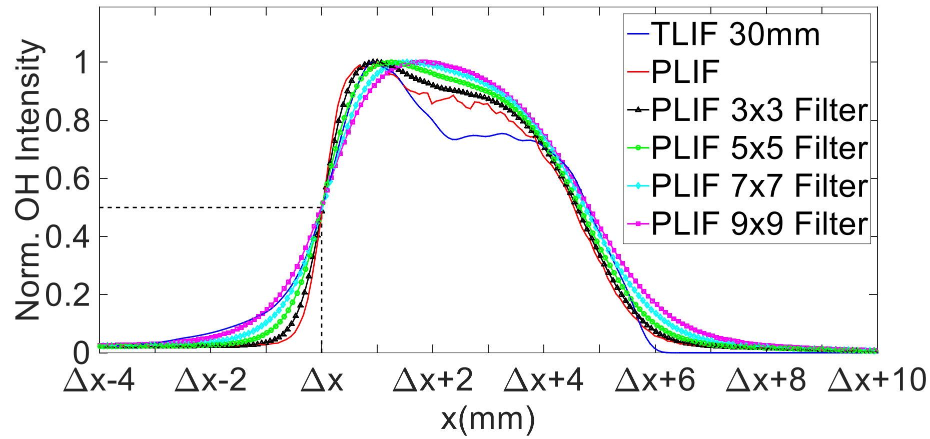
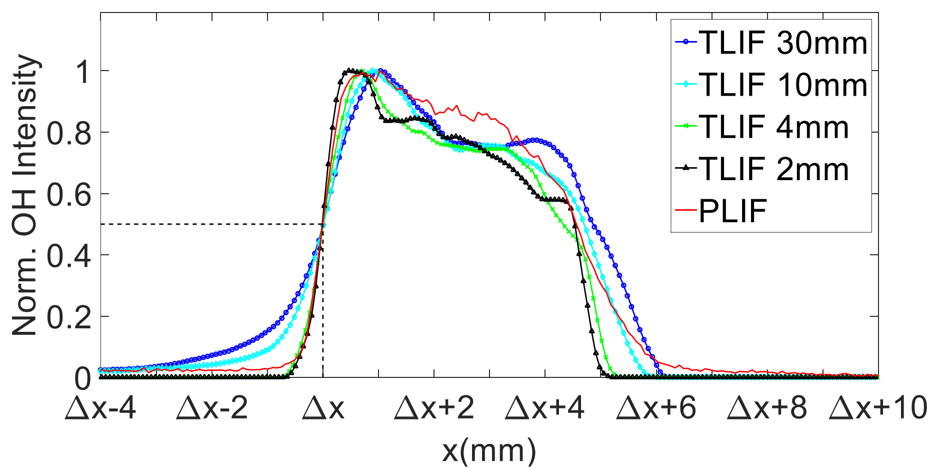
Comparison with 2D PLIF measurements

- 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





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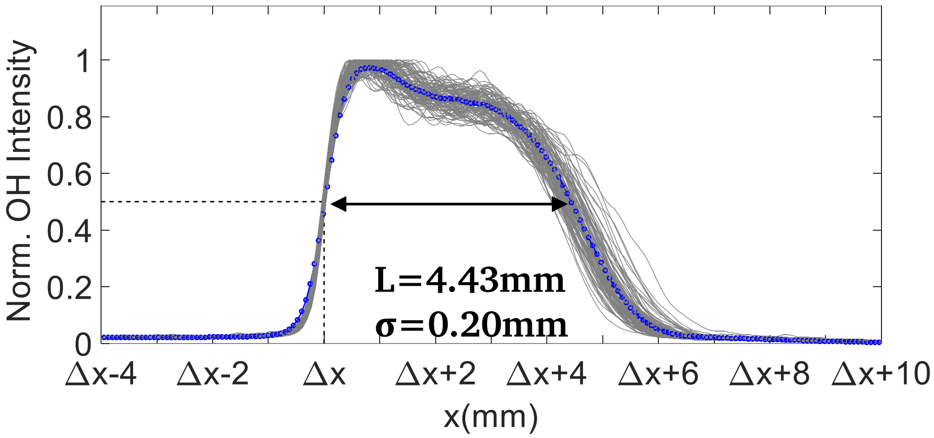
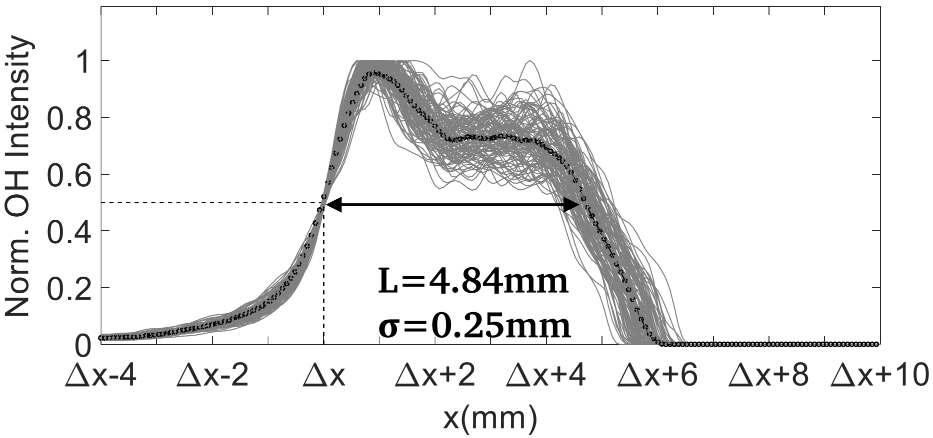
Comparison with 2D PLIF measurements

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



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

Length L at 50% intensity and its standard deviation σ



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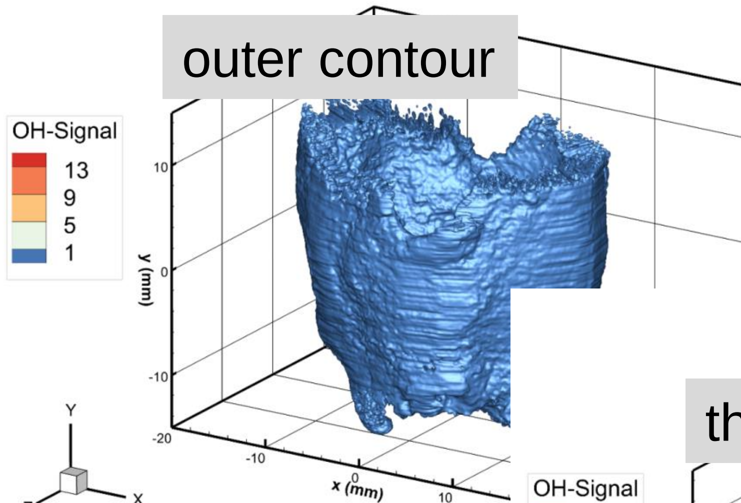
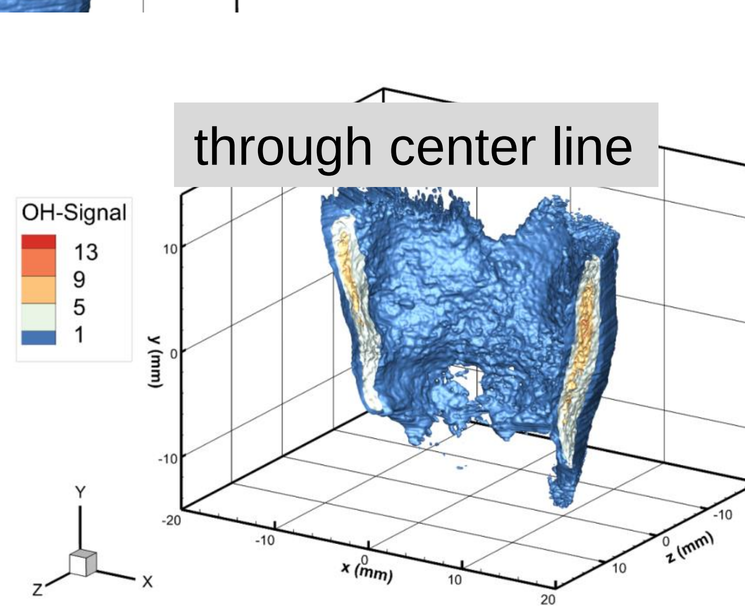
Turbulent lifted flame
Re 5000, voxel of 75^3 µm^3, no binning





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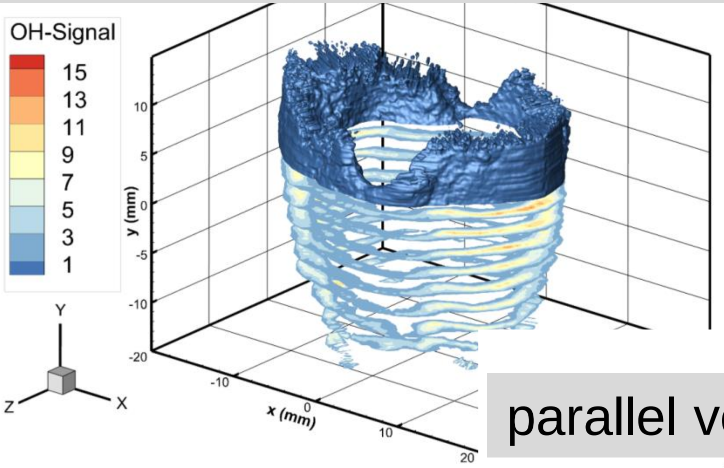
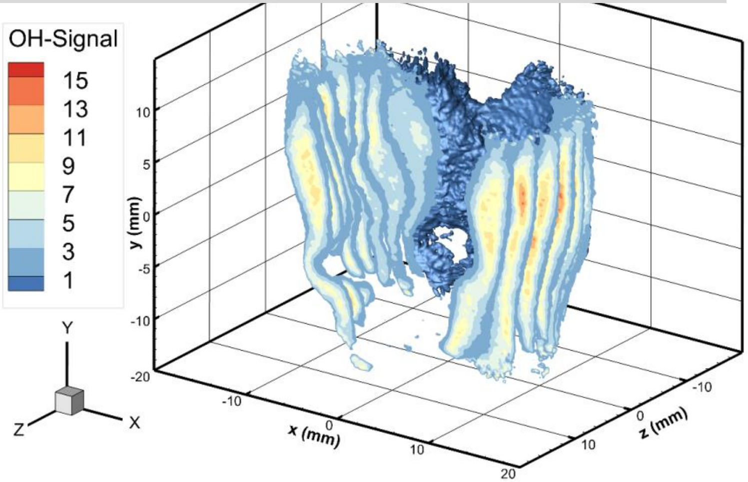
Turbulent lifted flame

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

parallel horizontral cross section



parallel vertical cross section



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Application to auto-ignition

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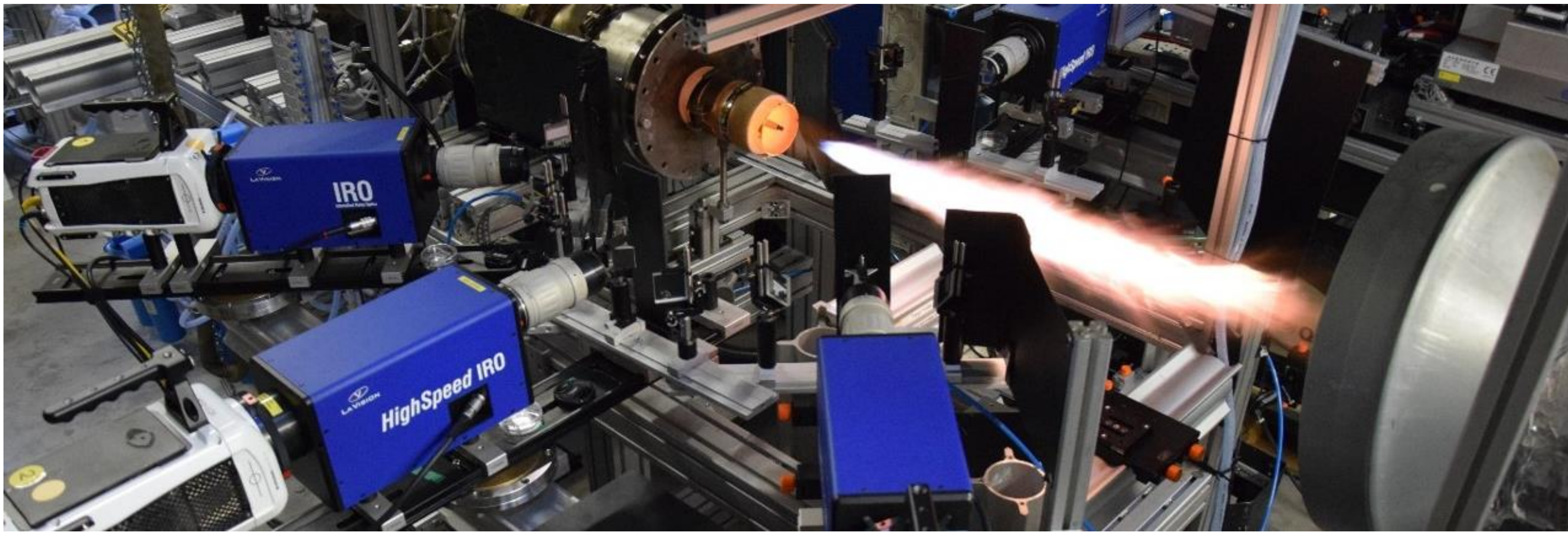
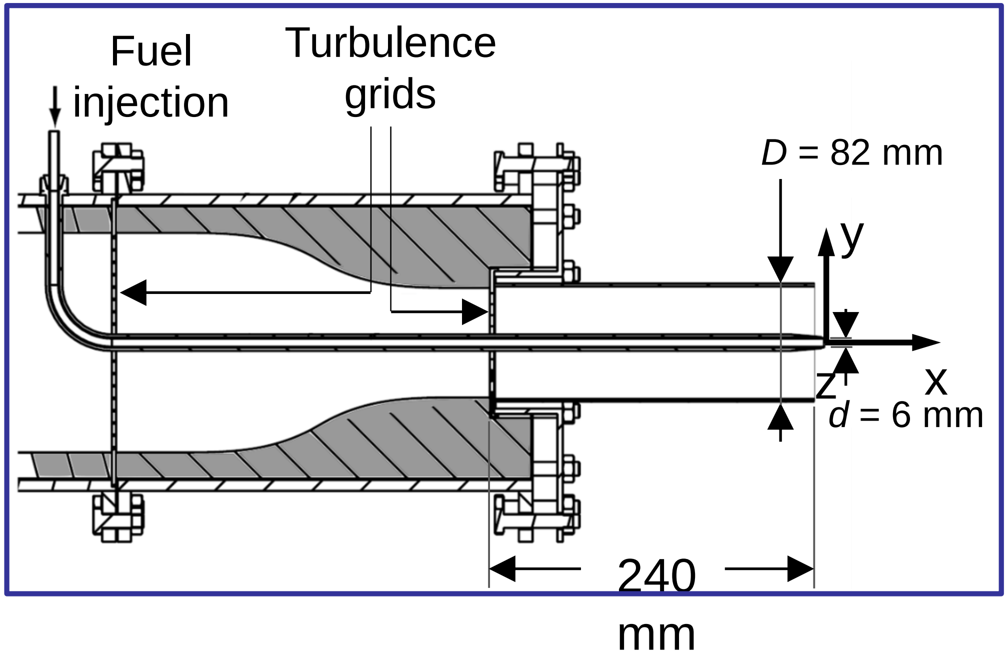
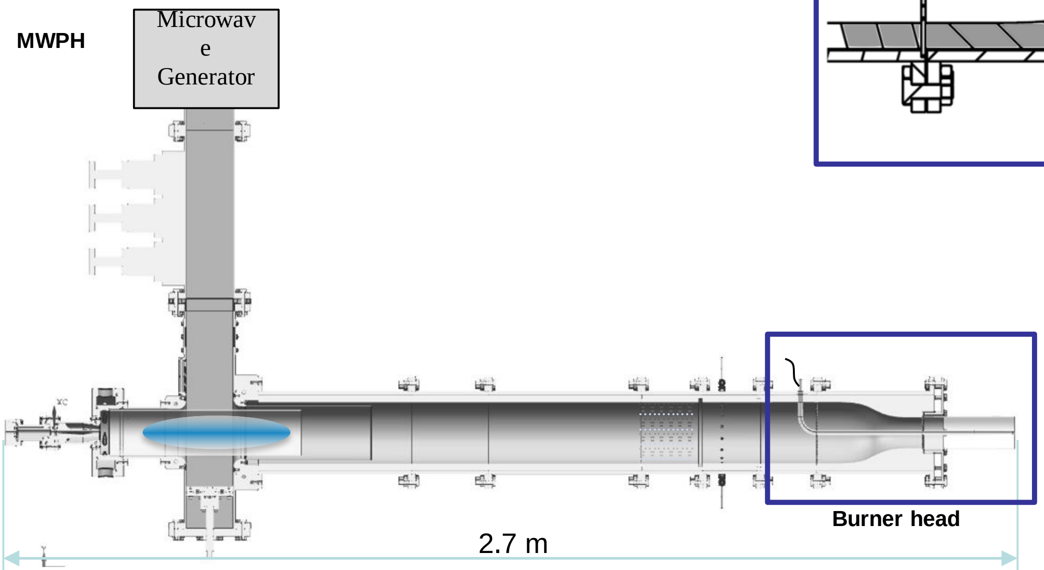


Johchi et int. Dreizler. Experiments in Fluids (2019) 60 (5):82
Pareja et int. Dreizler. Proc. Combust. Inst. (2019) 37 (2):1321-1328

75 kW Microwave Plasma Heater test rig

- Jet-in-Coflow configuration
- Continuous fuel injection
- High temperature (up to 1150°C) and high velocity (up 40 m/s) co-flow
- Controllable turbulence level





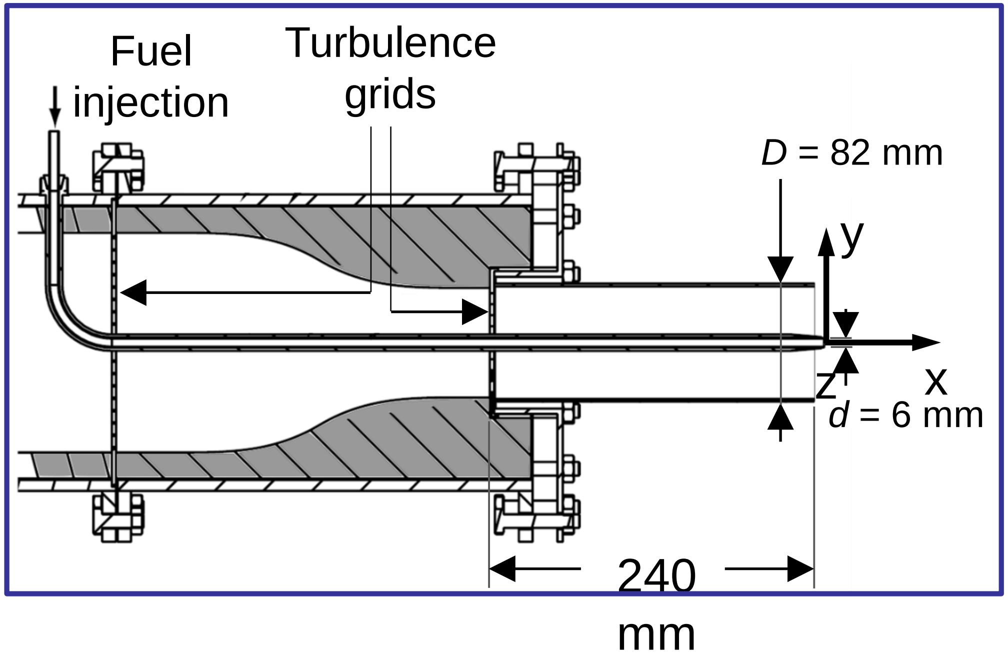
Operating conditions based on lift-off-height (LOH)

Fuel jet: CH_4

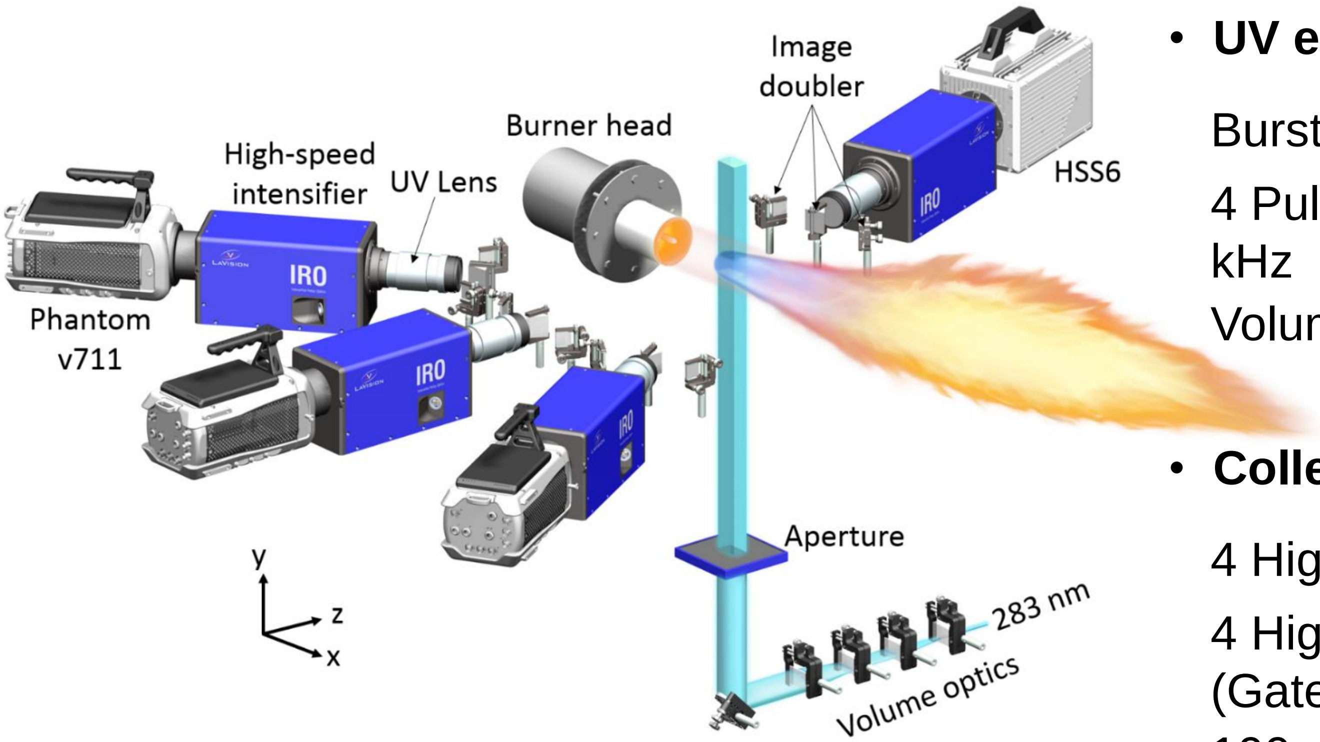
Re_{jet} [-]	T_{jet} [°C]	U_{jet} [m/s]	LOH [mm]
5000	450	69	76
10,000	320	99	85
15,000	260	123	94

Co-flow: Air (~1% NOx)

Re_{coflow} [-]	T_{coflow} [°C]	U_{coflow} [m/s]
10,000	1050	25



Experimental setup for high speed tomographic OH-LIF



- **UV excitation 283.01 nm**

  Burst Dye laser system

  4 Pulses, ~4 mJ/pulse at 10 kHz

  Volume 27x30x20 mm^3

- **Collection 320 ± 20 nm**

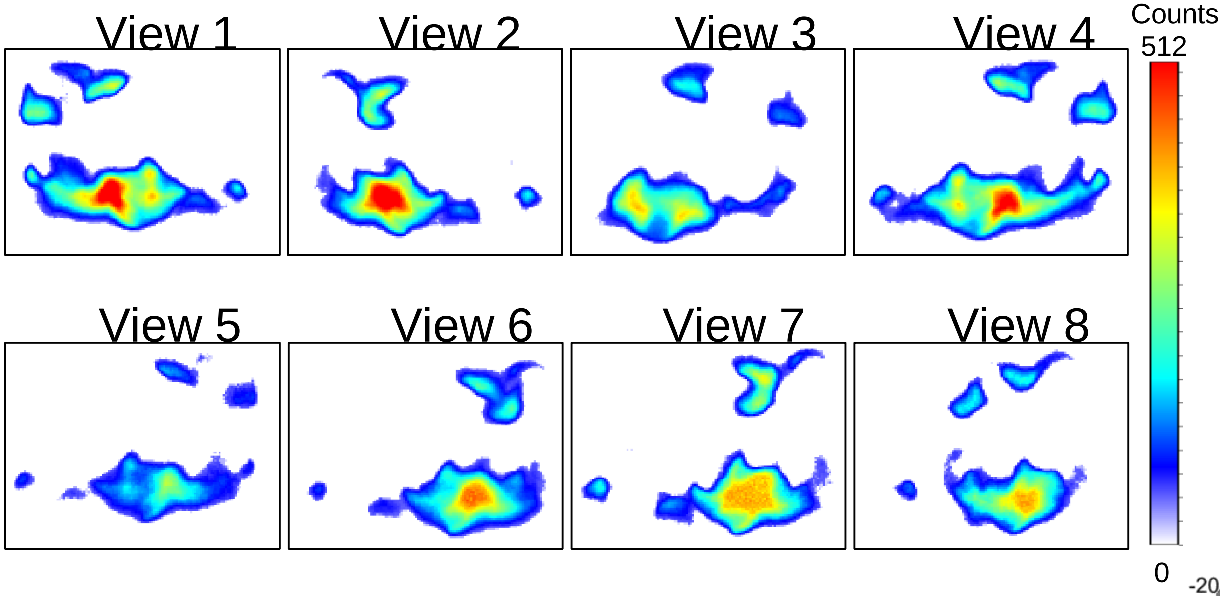
  4 High-speed cameras

  4 High-speed intensifiers (Gate: 200ns)

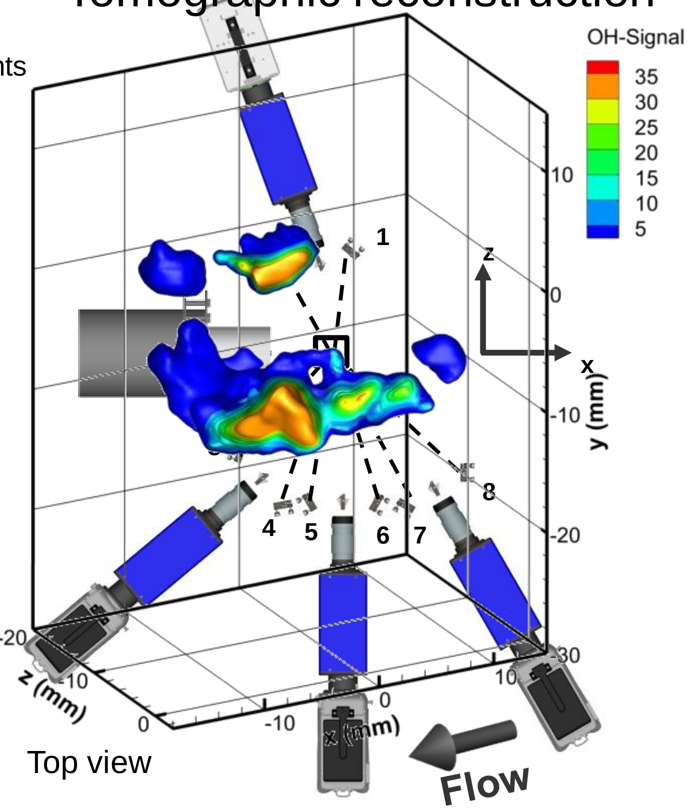
  100 mm UV lenses with image doubler

Tomographic reconstruction

Sample sequence of raw OH-LIF images

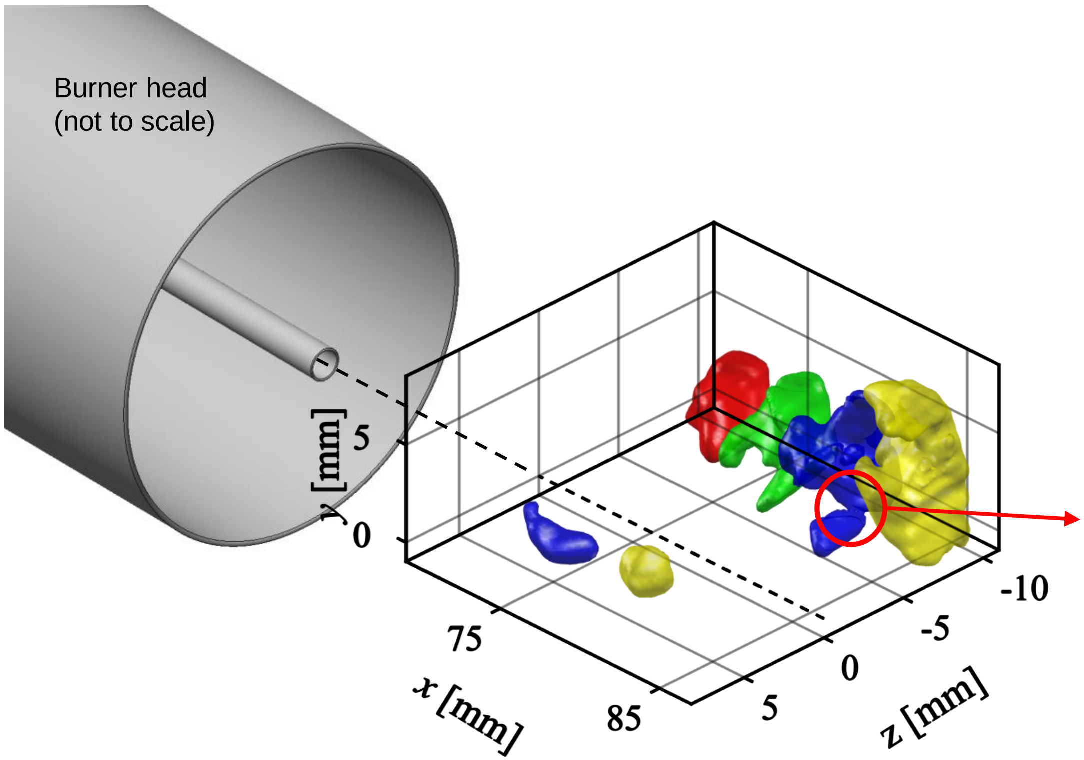


Tomographic reconstruction



- SMART algorithm (DaVis Software)
- 100 iterations, 3.7 million voxels (190 µm^3)
- Spatial resolution ~1.3 mm (from comparison with OH-PLIF)

Detected kernels: spatial and temporal evolution



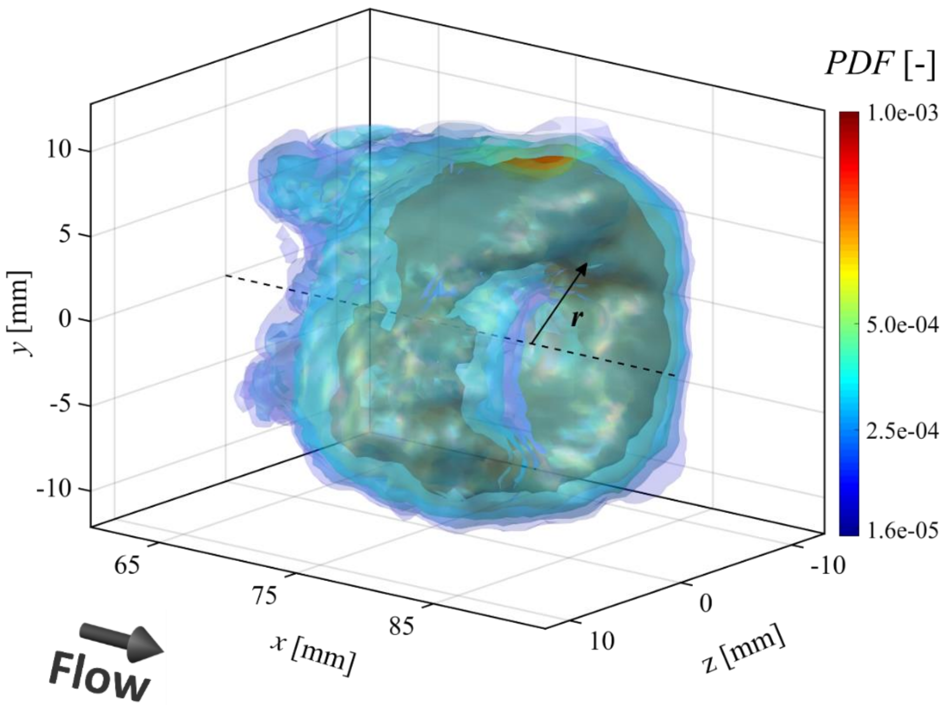
Example sequence, Re_{jet} = 15,000

- ***t_0*: an auto-ignition kernel detected**
- ***t_0 +100 µs*: kernel growing in size and convected with the flow**
- ***t_0 +200 µs* : a second independent kernel detected**

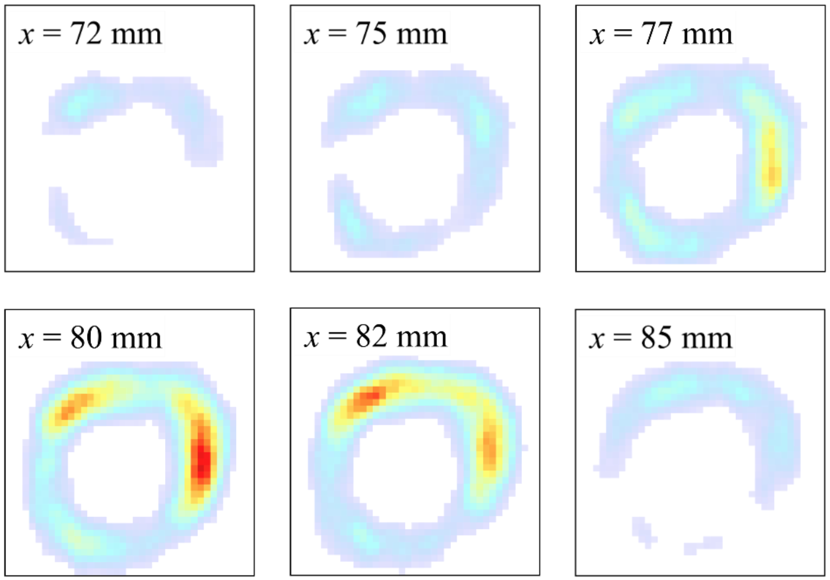
  Local extinction or secondary auto-ignition event
- ***t_0 +300 µs* : first detected kernel partially out of the measurement volume**

  Second detected kernel shrinking

Location of auto-ignition kernels

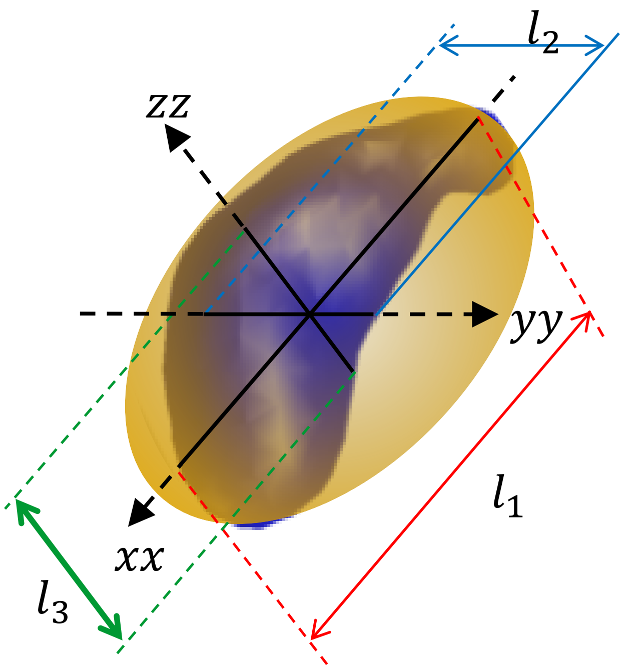


3D *Probability Density Function* of the volume occupied by 3300 auto-ignition kernels, Re_{jet} = 5000



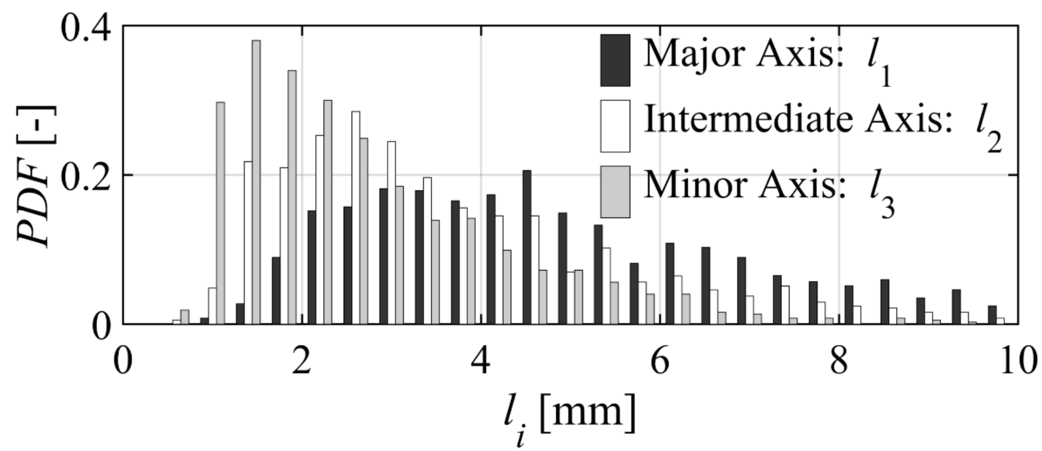
Corresponding 2D distributions on transverse planes along the x-axis

Size characterization of auto-ignition kernels



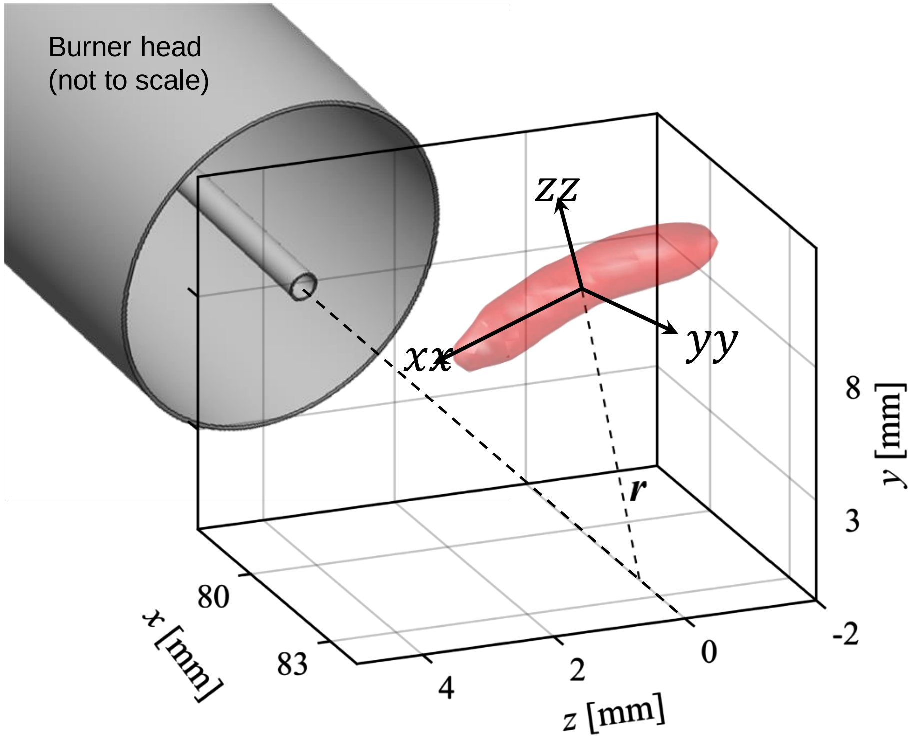
Example: isosurface of an auto-ignition kernel

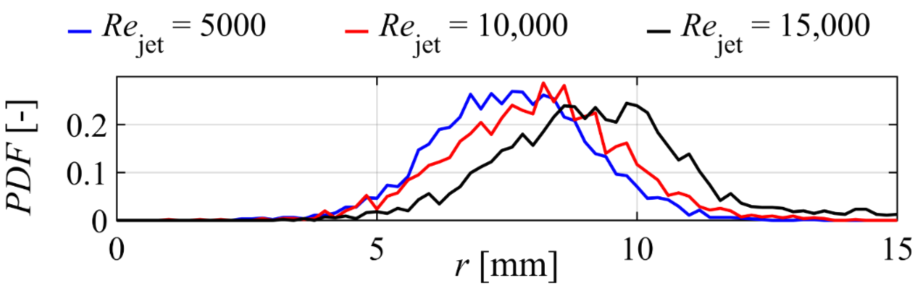
- Kernel-fixed coordinate defined by ellipsoid fitting
- Characteristic size of the kernels from Feret diameters
- Statistics only with the first appearance of the kernel



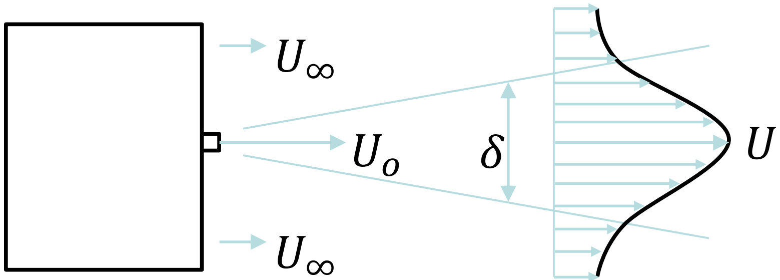
Size of auto-ignition kernels Re_{jet} = 5,000

Radial location of auto-ignition kernels



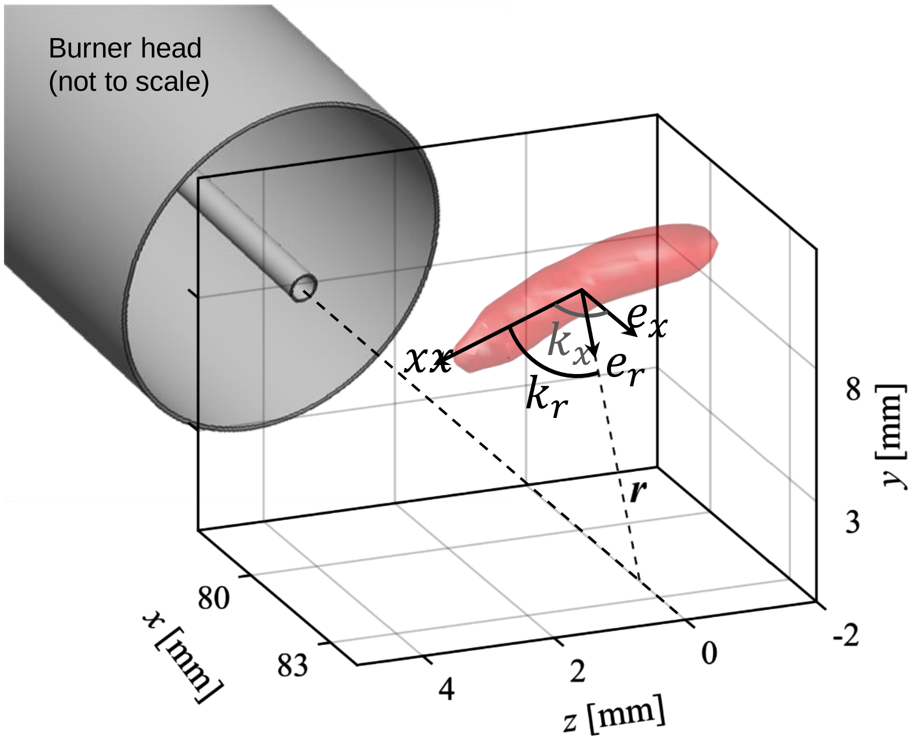


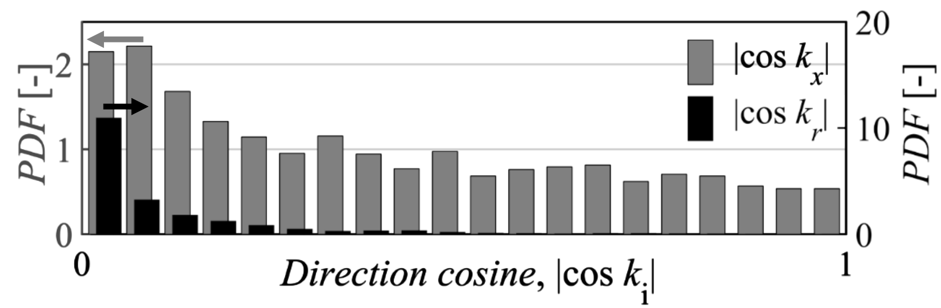
Radial position of auto-ignition kernels at different Re_{jet}

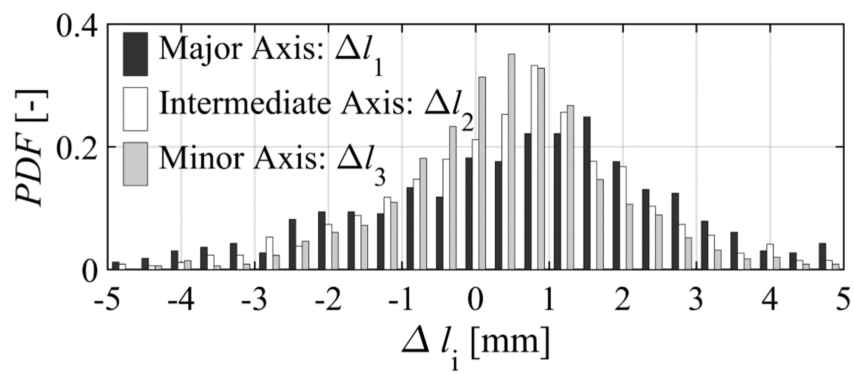


Spreading jet

Orientation of auto-ignition kernels







Change of the Feret diameters of auto-ignition kernels in 100 µs

- Auto-ignition kernels are preferentially orientated along the tangential direction with respect to the mean flow
- Evolution towards this same direction as the auto-ignition event progresses