Investigations of Soot Formation in an Optically Accessible Gasoline Direct Injection Engine

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Introduction

In recent years a change regarding the fuel injection strategy of gasoline engines has emerged. An increasing number of automotive manufacturers offer direct injection gasoline engines in addition to the established engines with port-fuel injection and external mixture formation. Due to more and more restricted emission limits it is essential to gain a deeper understanding of the underlying reaction and formation processes of soot and other pollutants. In addition to the limited values for the particle mass a limitation of the particle number will be introduced in Europe in 2014 [1]. Without further measures these limits will be hard to achieve. Consequently, the importance of soot as a pollutant is recognized to be a serious challenge to engine developers. To optimize the combustion process it is essential to evaluate the particle formation and distribution by means of qualified and reliable measurement techniques. In this context, it is necessary to perform in-cylinder measurements in an optically accessible engine next to measurements in the exhaust gas system to gain a detailed view of the cause-and-effect chain.

Experimental Setup

The engine used in this study was a single cylinder spark-ignition research engine with a direct-injection, spray-guided combustion process. The injection valve was located in the center of the cylinder head while the spark plug was positioned in-between the exhaust valves. Details concerning this engine can be found in [2], [3]. The optical techniques allow the non-intrusive visualization and measurement of in-cylinder processes. In-cylinder gas flow and injection behave nearly unchanged compared to a conventional thermodynamic engine. Vaporization and combustion may be slightly altered owing to the thermal conductivity of the glass inserts.

Laser-induced Fluorescence (LIF)

In a first step it is important to gain an increased knowledge about the sources of soot formation inside the combustion chamber. Therefore high-speed laser-induced fluorescence (LIF) was applied in order to characterize the mixture formation and to detect the surface areas which may be wetted. Conventional LIF measurements operate at low repetition rates recording only one image per engine cycle. High-speed measurements provide the opportunity to observe the mixture formation over a broad range of crank angles within one individual cycle. The focus of this measurement concept is the visualization of the liquid and vaporized fuel by recording the laser-induced fluorescence. One result of this advanced measurement approach is the identification of the different sources of soot formation. Discrete regions with strong wall-wetting are identifiable which in turn influence soot formation.

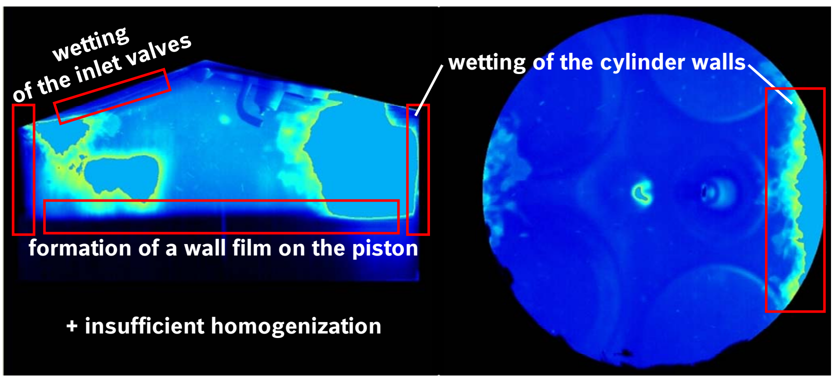


Fig. 1: Typical soot sources which can occur in a gasoline direct injection engine (left: side view in the combustion chamber / right: view from below)

In Figure 1, the main regions with wall-wetting are shown such as different parts of the combustion chamber like the piston, cylinder walls, and the inlet valves. The measurement technique not only detects wall-wetting, but also insufficient mixture homogenization during the intake and compression stroke.

High-speed Flame Analysis of the Combustion

To gain a fundamental understanding of the soot particle formation and distribution a measuring concept using the thermal emission of carbon particulates was developed. In detail, the aim was to identify the sources of soot formation and to evaluate the influences of engine speed and injection timing. By using an appropriate optical filter to analyze the spectral region above 850 nm the emission of the soot particles can be separated from the emission lines of a hydrocarbon flame [4]. This concept uses two high-speed cameras to analyze the combustion by recording the in-cylinder processes from the side and from the bottom of the combustion chamber. Figure 2 shows the influence of the injection timing. It can be clearly seen that an early injection leads to pool fires and a sooting combustion. In contrast, a late injection leads to a wetting of the inlet valves. Hence, reducing the emission of soot particulates the sensitivity of the injection timing needs to be investigated in detail.

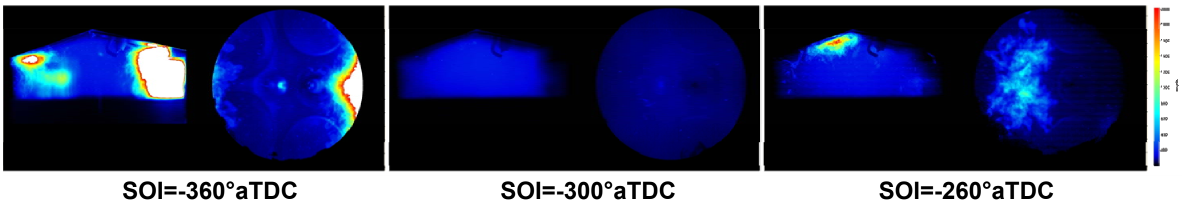


Fig. 2: High-speed flame analysis of the injection timing
(left: side view in the combustion chamber / right: view from below)

Laser-induced Incandescence (LII)

Laser-induced incandescence (LII) has become an established method for measurements of soot concentration and primary particle sizes. In recent years this method has been used in a large number of applications and different evaluation strategies have been developed. LII is a non-invasive approach with high spatial and temporal resolution [5]. Particles are rapidly heated up to 4000 K using a pulsed laser. Subsequently broadband thermal radiation from the hot particles is recorded (compare Fig. 3).

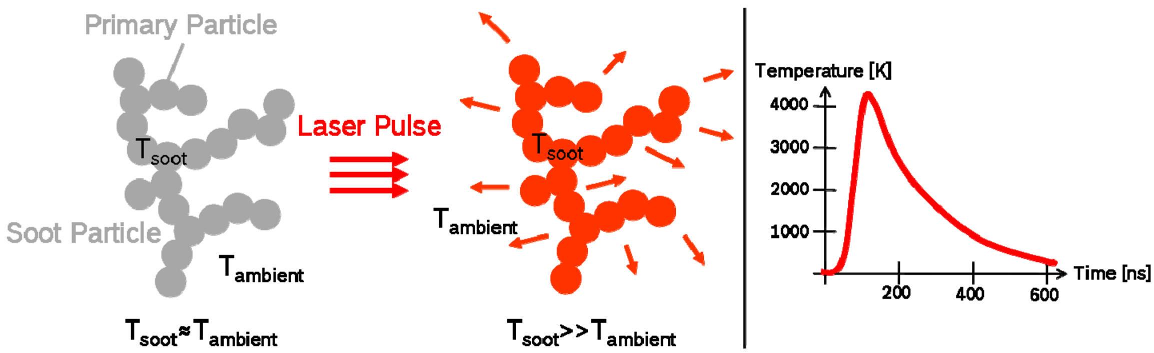


Fig. 3: Measurement Principle of the Laser-induced Incandescence (LII)
(left: side heating of the soot particles / right: exemplary temperature course)

Two methods have been established for the analysis of the thermal radiation emitted by hot soot particles: the time-resolved analysis of the light emission (TR-LII) enables the determination of the particle sizes at high repetition rates. In contrast, measurement of the two-dimensional light intensity (2D-LII) provides information of the soot volume fraction. Applying the first method mainly photomultipliers are used due to their sensitivity and time-resolution. As a consequence this approach is typically a point measurement. Analyzing the soot volume fraction a laser light sheet technique in combination with a high resolution camera can be applied which allows for a 2D measurement. Two particularly appealing features of 2D-LII are its conceptual simplicity and ease of implementation [6] Determination of the soot particle size is based on complex physical models, considering heating by absorption of laser energy, oxidation and annealing and cooling by heat conduction to the surroundings, sublimation and radiation [7] [8] [9]. A comparison of time-resolved LII, based on the model described by H.A. Michelsen [8], with an Engine Exhaust Particle Sizer (EEPS) [10] was performed. Good agreement between the different techniques was achieved and can be found in [3].

Exemplary results from the measurements using 2D-LII are shown by Figure 4. In this context the temperature of the engine and the air/fuel-ratio has been varied.

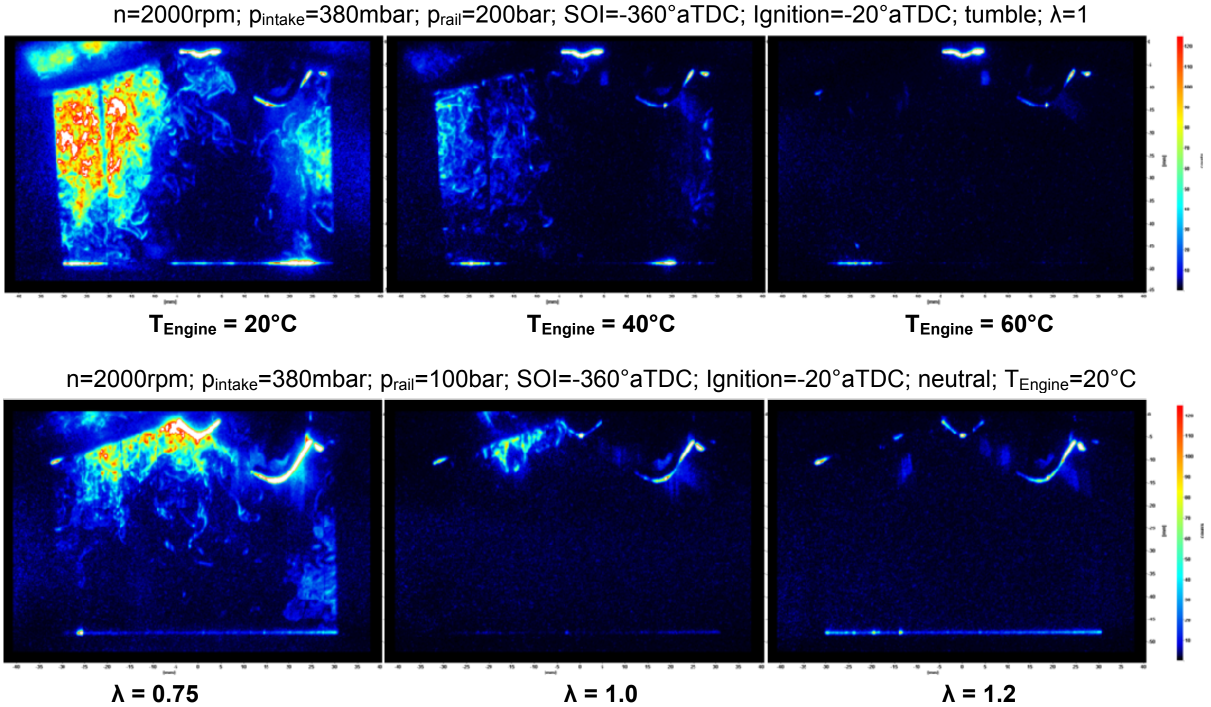
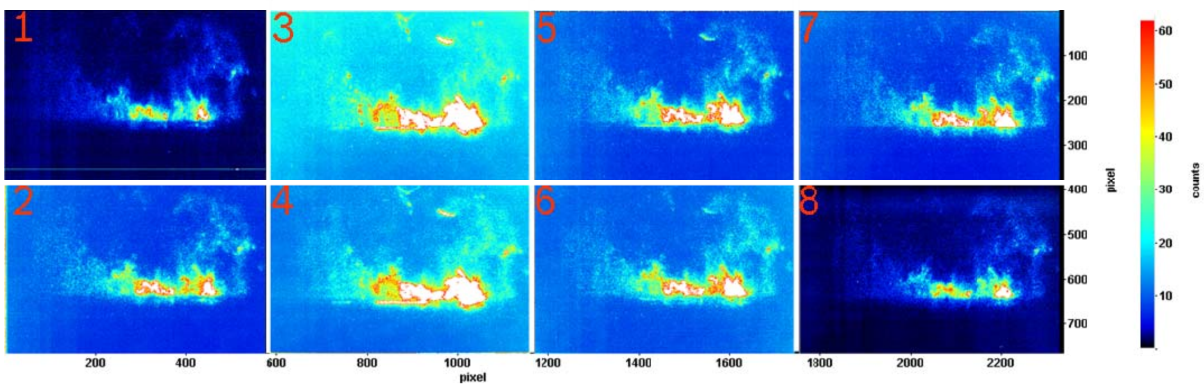


Fig. 4: 2D-LII results: Variation of the engine temperature (upper row) and the air/fuel-ratio (lower row)

Next to LII further exhaust gas measurements systems were conducted. In this context, the above mentioned Engine Exhaust Particle Sizer (EEPS) was applied in combination with the analysis of the filter smoke number (FSN) [11].

New approach: 2D Time-Resolved LII

This new approach is based on the idea to combine two-dimensional and time-resolved LII to one single measurement technique. With this concept it is possible to determine the soot volume fraction and the particle sizes simultaneously within the same engine cycle. The experimental procedure is as follows: a series of images is taken using an ultra-high-speed camera (Hadland Imacon 468) during the cooling process of the heated particles. The first image has to be recorded before the laser-pulse heats up the particles. Thus the soot luminescence can be subtracted from the remaining frames. Using the pixel-wise intensity of the following frames a corresponding decay curve can be determined for each pixel. Comparing this curve to a simulated decay curve a local particle size distribution can be derived. As an example, a sequence of images which shows the cooling process can be seen in Figure 5. A side view inside the combustion chamber is shown and a pool fire can be recognized.



n=2000rpm; p_{intake}=380mbar; SOI=-19°aTDC; Ignition=-15°aTDC; λ=1.2; T_{Engine}=20°C

Fig. 5: 2D-TR-LII: Sequence of eight pictures recorded during the cooling process

Conclusions

Different laser optical measurement techniques have been used successfully in combination with an optically accessible gasoline direct injection engine to gain a detailed view of the in-cylinder soot formation and source regions. The studies include systematic variations of engine and injection parameters. It was observed that the soot formation and emission strongly depends on engine parameters like injection timing and injection strategy. A new measurement approach was introduced enhancing the 0D time-resolved LII to 2D time-resolved LII enabling the 2D evaluation of soot volume fraction and particle size distribution simultaneously.

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June 27th, 2011

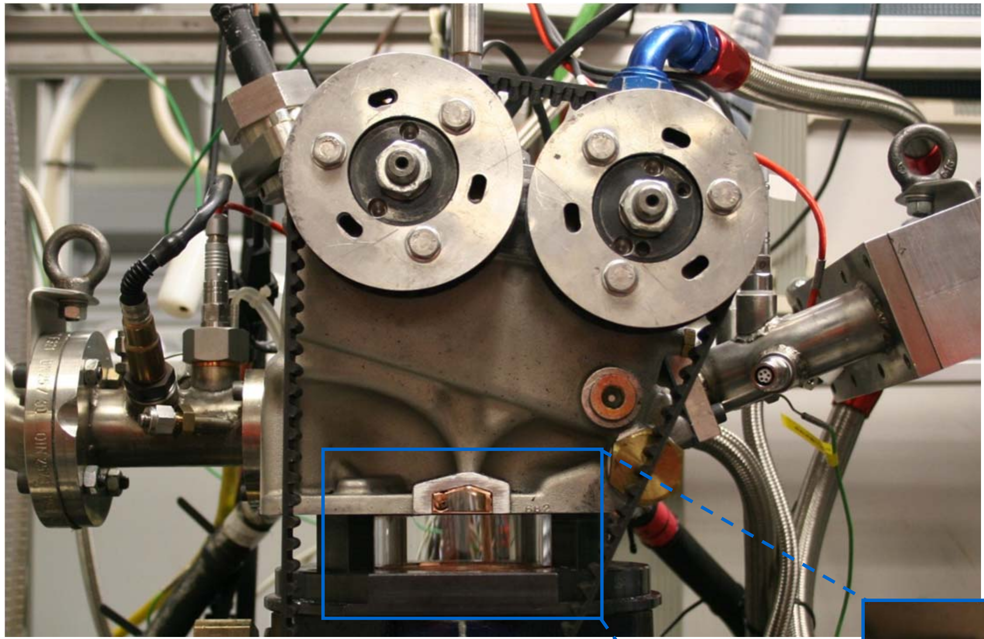
Outline

- Introduction
- Optically Accessible Gasoline Direct Injection Engine
- Applied Measurement Techniques
  - Mixture Formation
  - Combustion
  - Emission
  - Outlook: Innovative Measurement Approach
- Summary

Introduction

- <u>Background:</u> introduction of the European EU6 emission limits in 2014
  → particle number and mass will be limited for gasoline engines
- detailed investigations concerning the soot formation necessary
- <u>Objective:</u> gaining a deeper understanding of the underlying reaction and formation processes of soot in order to minimize the particle emission
- qualified and reliable in-cylinder measurement technique required
- **<u>Intention:</u> identification and application of measurement techniques to characterize the particulate emission of gasoline engines**

Optically Accessible Gasoline Direct Injection Engine



Single Cylinder Research Engine

- Stroke/Bore: 86/82mm (454.2 cm^3)
- Compression Ratio: 9.60
- Valves: 4

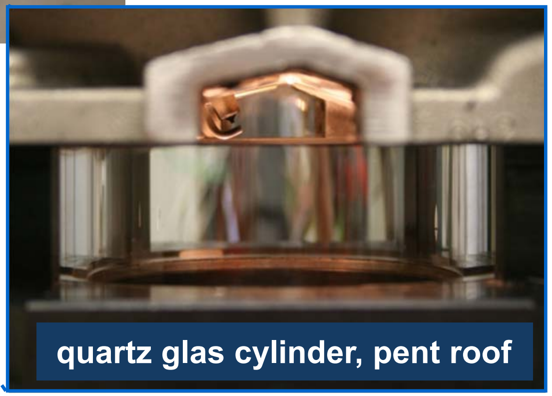
Combustion Technique

Gasoline Direct Injection, spray guided

- vertical injector position
- variable charge motion

Optical Access:

- Piston Crown
- Quartz Glas Cylinder
- Pent Roof Windows



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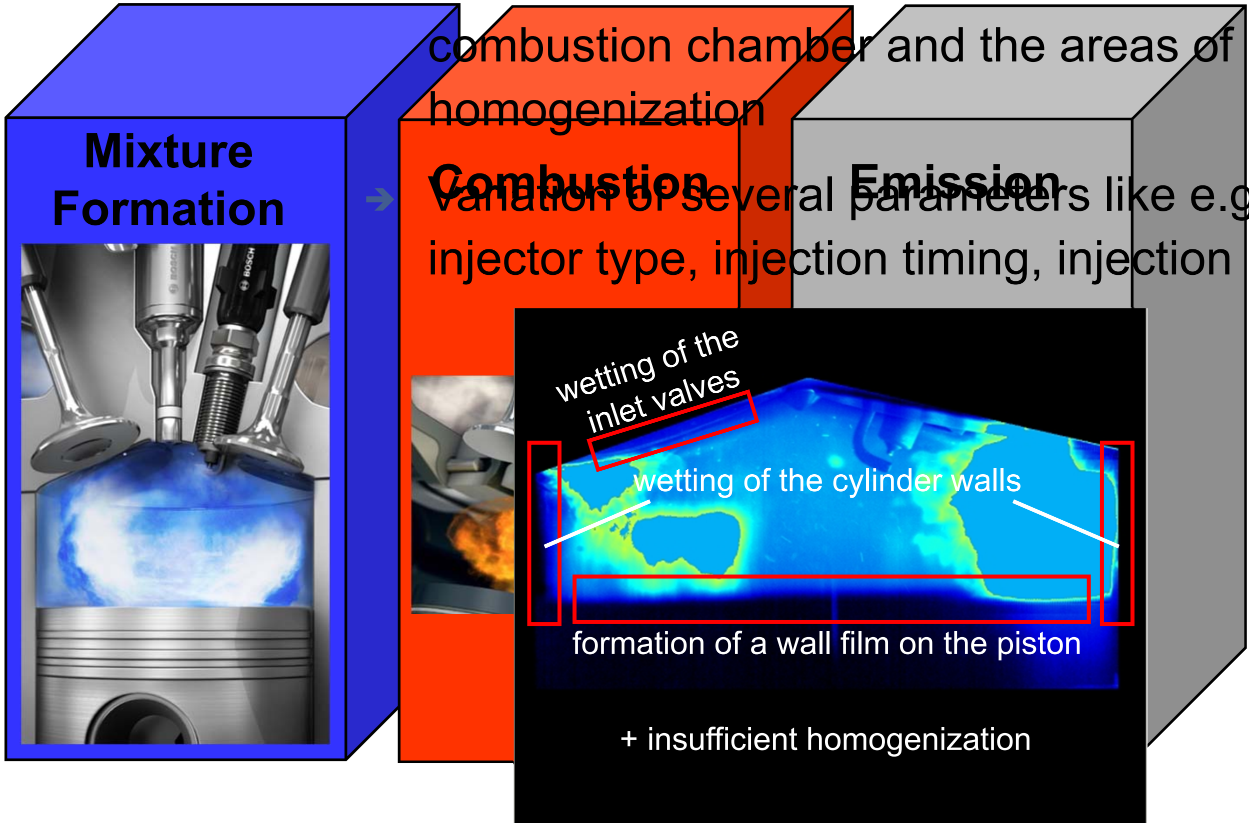
Applied Measurement Techniques:

Fields of interest concerning the particle formation:

- ➔ (Highspeed) Laser-induced Flourescence (LIF)
- ➔ Visualization of the wetted surfaces in the combustion chamber and the areas of insufficient homogenization
- ➔ Variation of several parameters like e.g. injector type, injection timing, injection pressure



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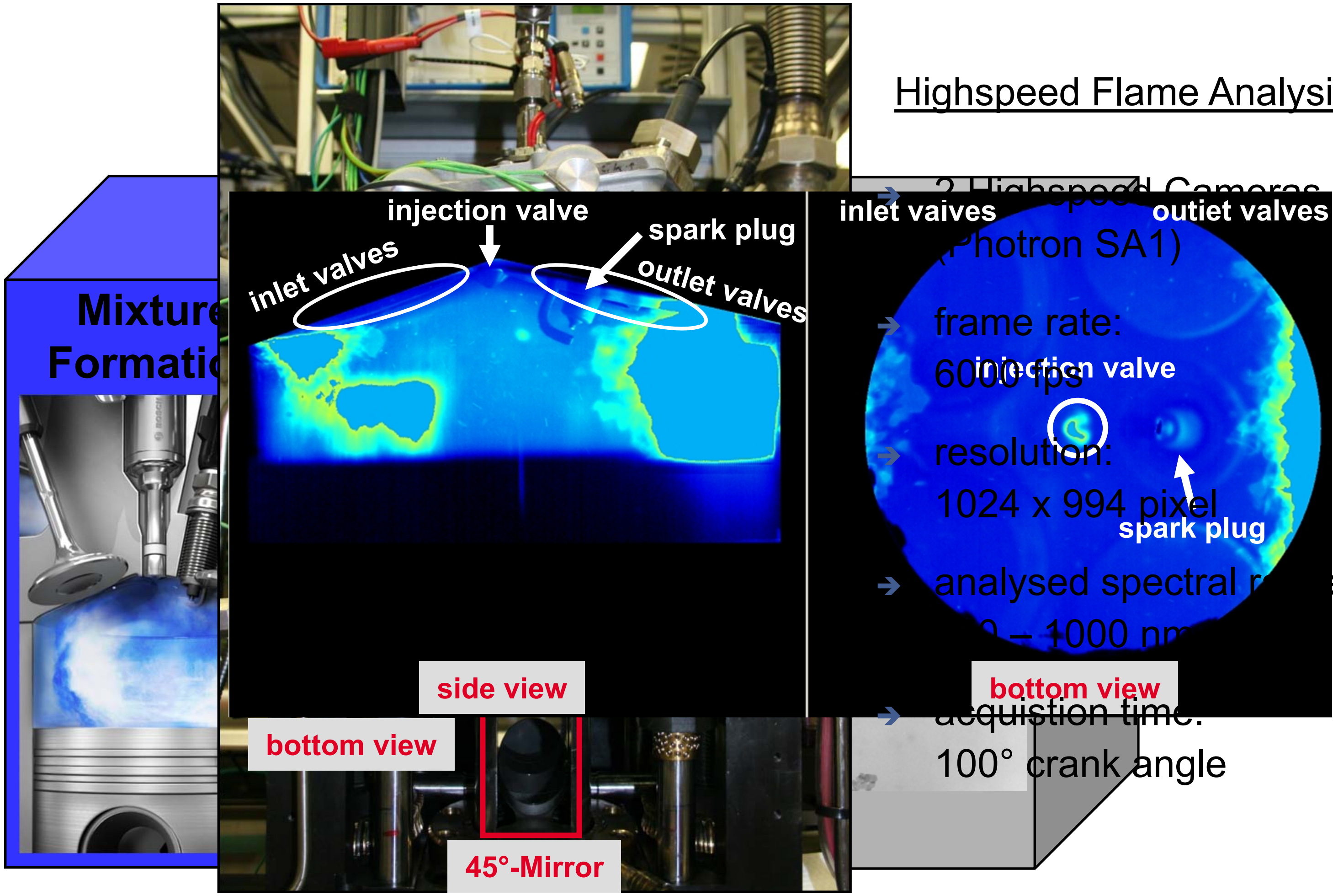
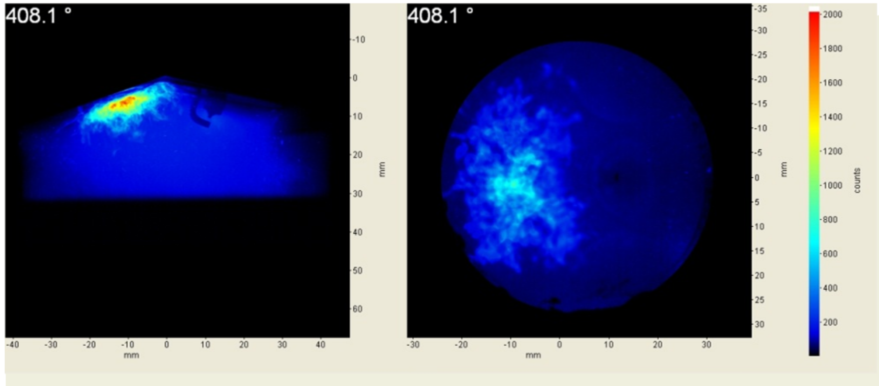


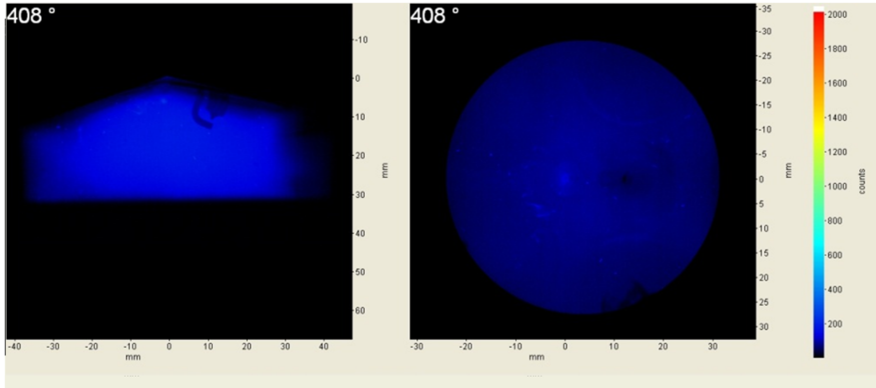
<u>Highspeed Flame Analysis:</u>

- 2 Highspeed Cameras (Photron SA1)
- frame rate: 6000 fps
- resolution: 1024 x 994 pixel
- analysed spectral range: – 1000 nm
- acquistion time: 100° crank angle

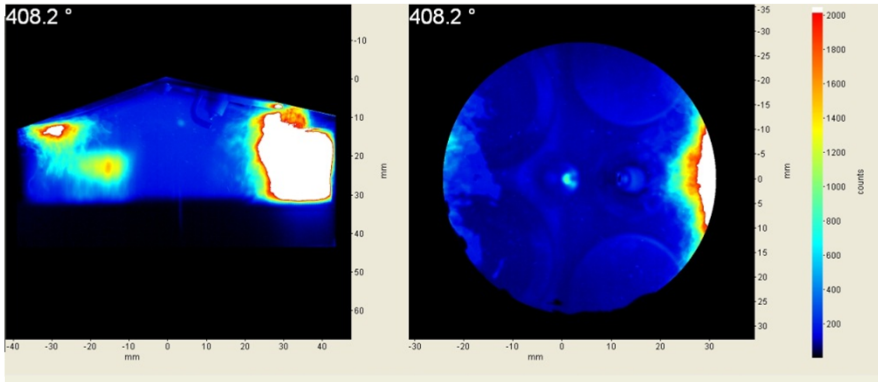
Combustion



Injection=260°BTDC



Injection=300°BTDC



Injection=360°BTDC

n=2000rpm
p_{mi}=2,8bar
p_i=100bar
λ=1,0
Ignition=25°BTDC
T_{Engine}=20°C

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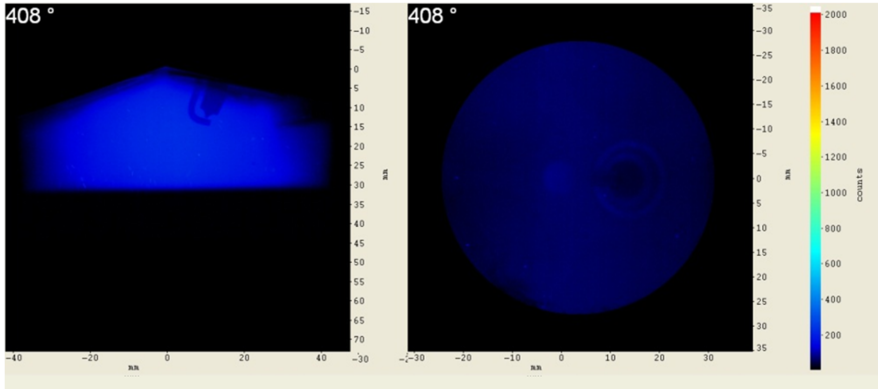
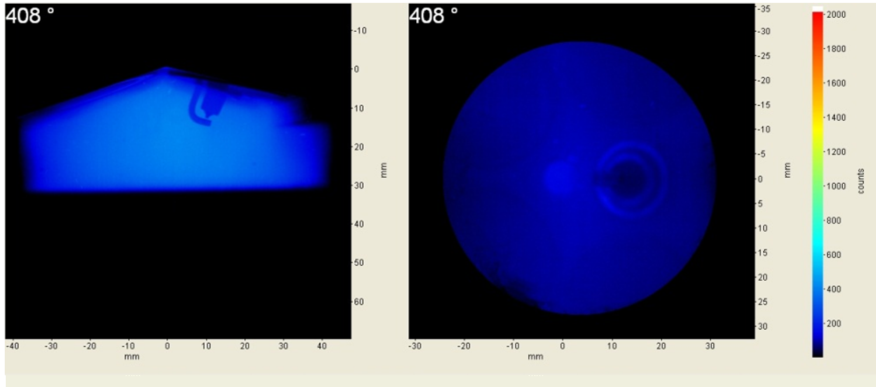
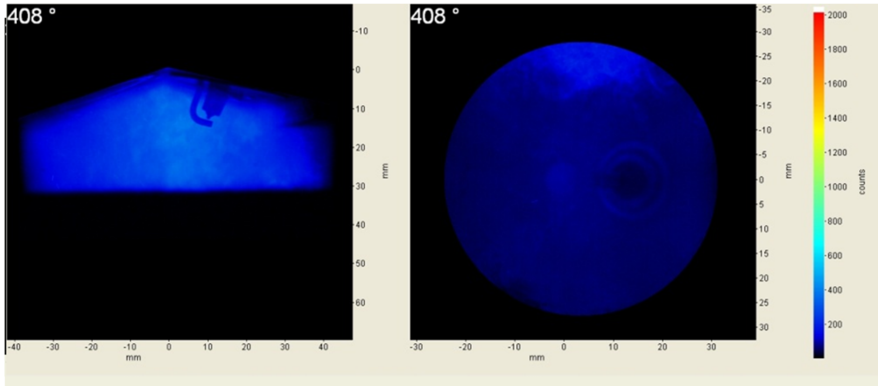
Combustion



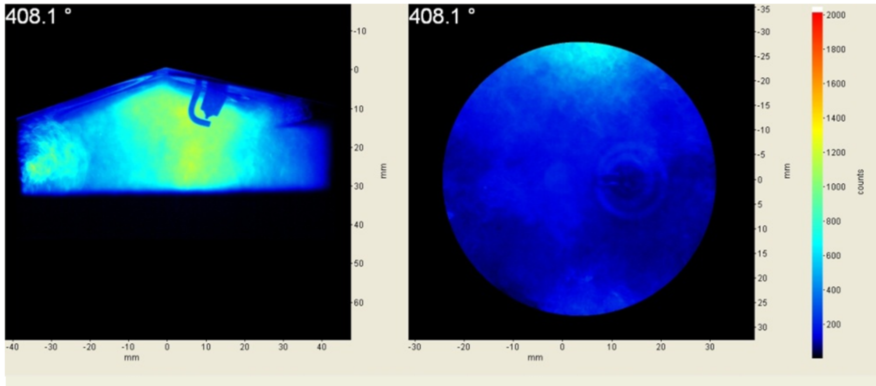
λ=1,2



λ=1,0



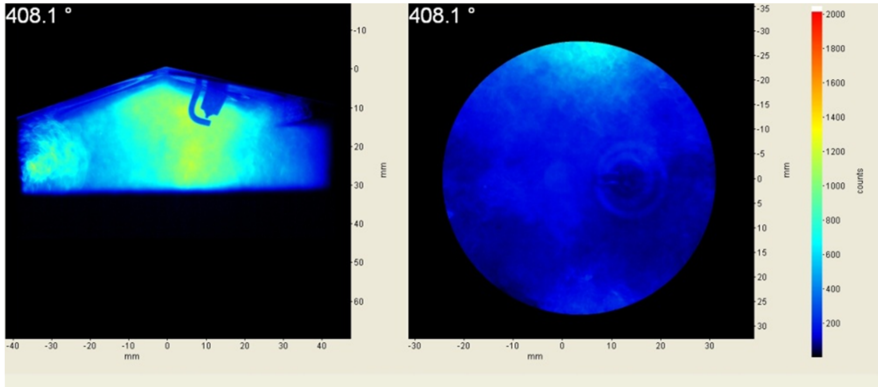
λ=0,8



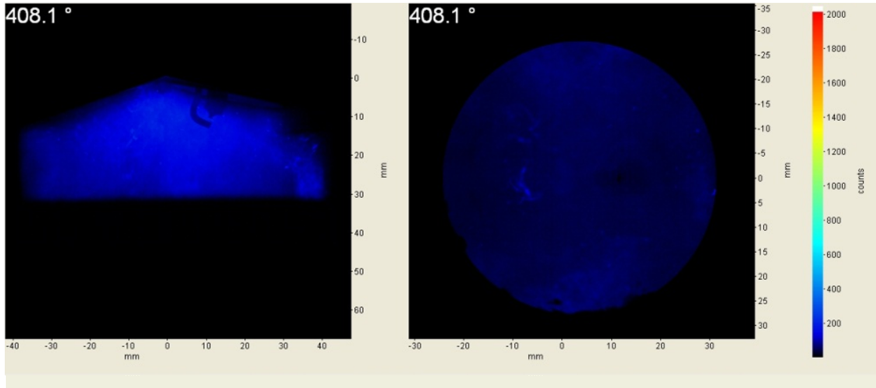
λ=0,75

n=2000rpm; p_{mi}=2,8bar; p_i=100bar; Injection=300°vZOT; T_{Engine}=20°C

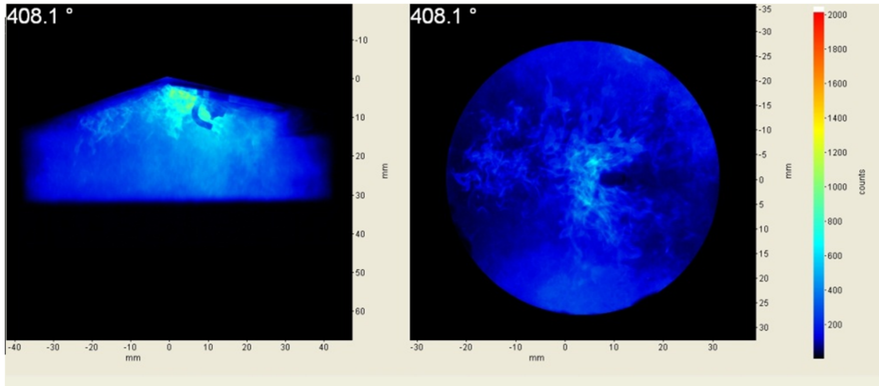
Combustion



Injector Type I



Injector Type II

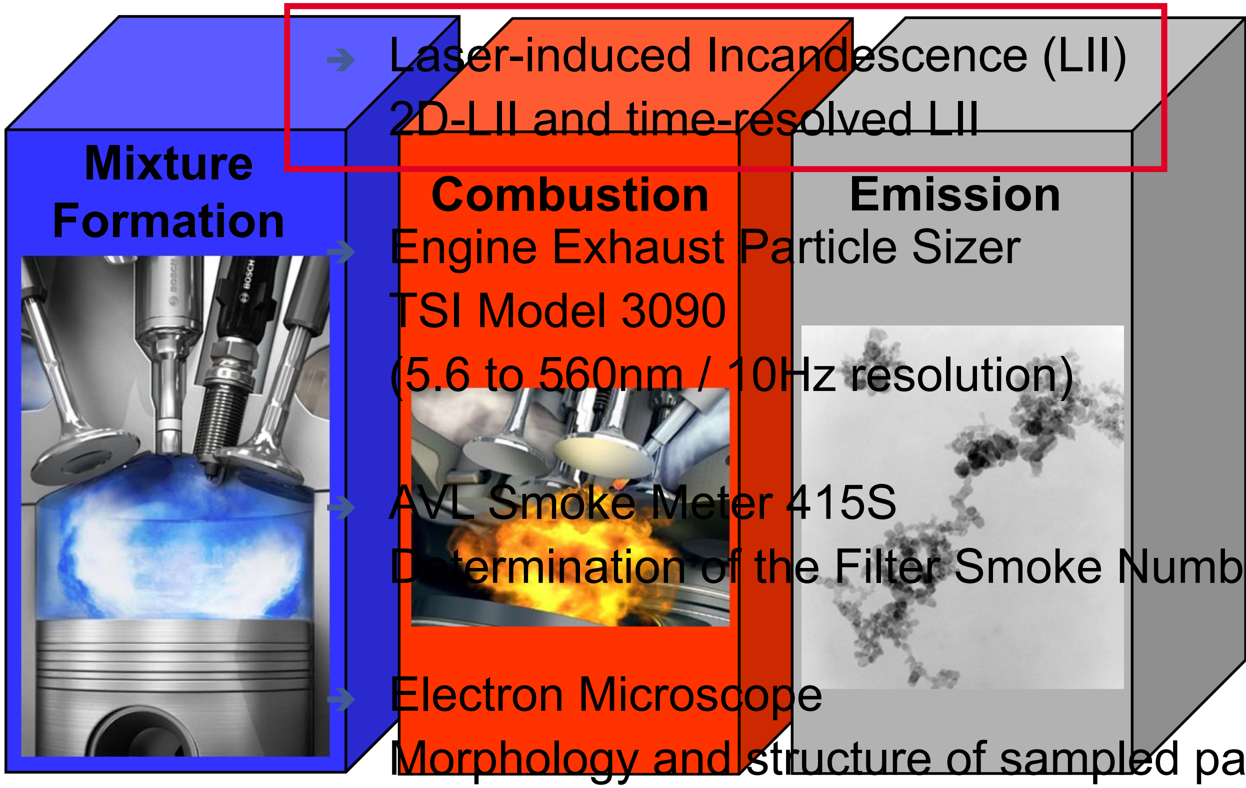


Injector Type III

n=2000rpm
p_{mi}=2,8bar
p_i=100bar
Injection=300°vZOT
T_{Engine}=20°C

Emission

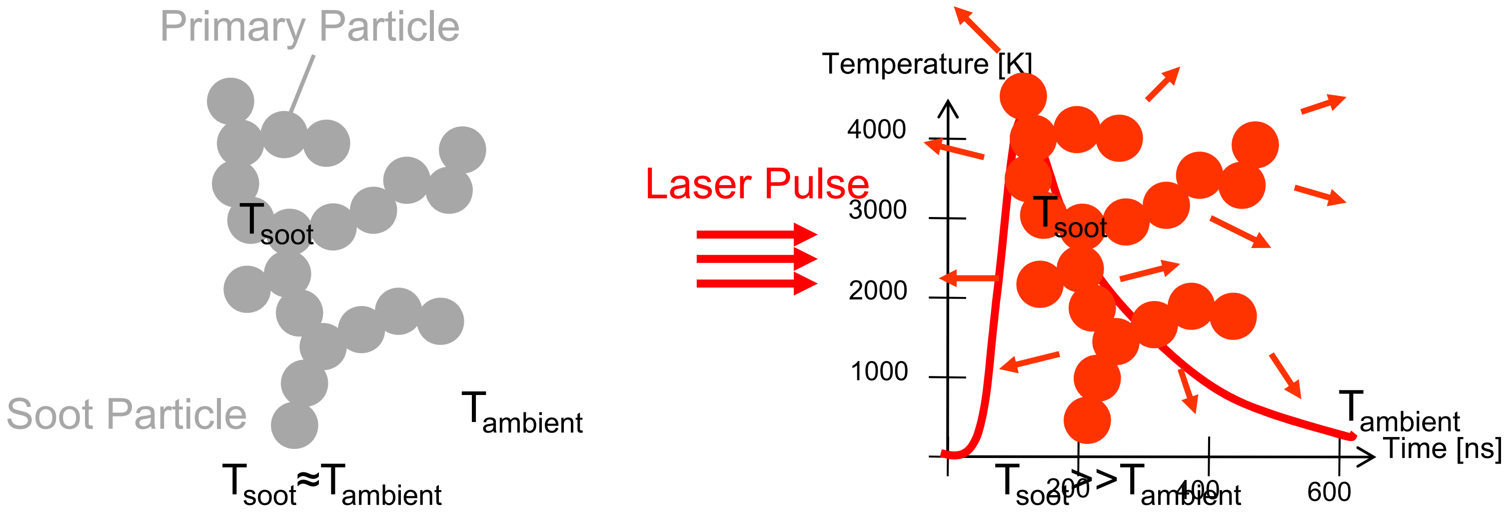
Applied Measurement Techniques:



- Laser-induced Incandescence (LII)
  2D-LII and time-resolved LII
- Engine Exhaust Particle Sizer
  TSI Model 3090
  (5.6 to 560nm / 10Hz resolution)
- AVL Smoke Meter 415S
  Determination of the Filter Smoke Number (FSN)
- Electron Microscope
  Morphology and structure of sampled particles

Emission

Laser-induced Incandescence (LII) – measurement principle:



- ➔ pulsed laser heats soot particles (up to 4000K)
- ➔ particles glow and cool down afterwards
- ➔ two possibilities to detect the resulting blackbody emission:
  - time-resolved → measurement of particle sizes
  - two-dimensional → measurement of soot volume fraction

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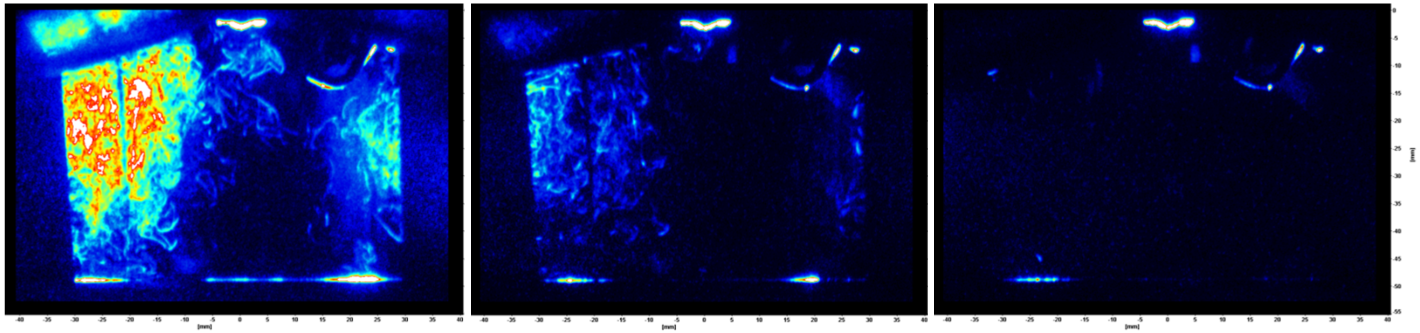
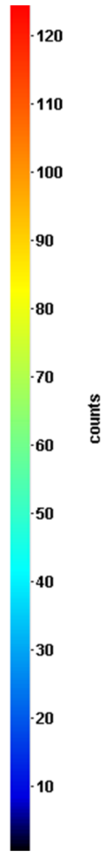
Emission

Example: Influence of the Engine Temperature

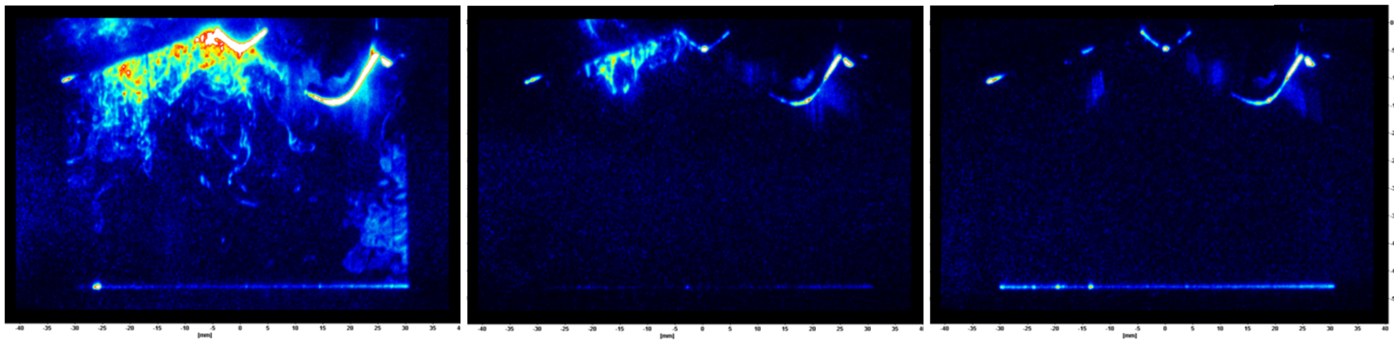


T_{Engine} = 20°C T_{Engine} = 40°C T_{Engine} = 60°C

[n=2000rpm; p_{intake}=380mbar; p_{rail}=200bar; SOI=-360°aTDC; Ignition=-20°aTDC; tumble; λ=1]



Example: Influence of the Air/Fuel-Ratio



λ = 0.75   λ = 1.0   λ = 1.2

[n=2000rpm; p_{intake}=380mbar; p_{rail}=100bar; SOI=-360°aTDC; Ignition=-20°aTDC; neutral; T_{Engine}=20°C]

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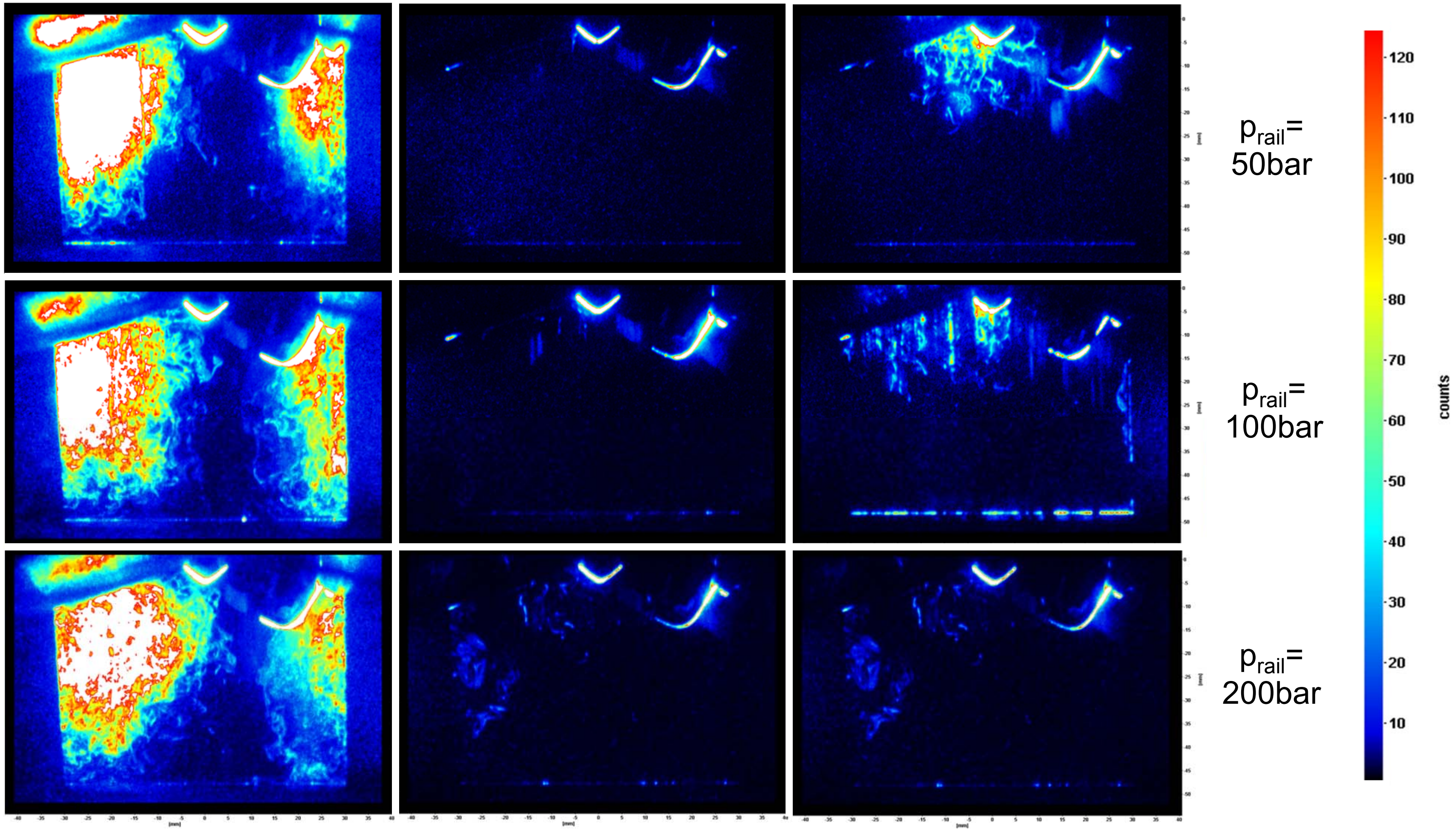
Emission



SOI=360°vZOT SOI=300°vZOT SOI=260°vZOT

[n=2000U/min; p_{intake}=380mbar; Ignition=-25°aTDC; λ=1; tumble; T_{Engine}=20°C]

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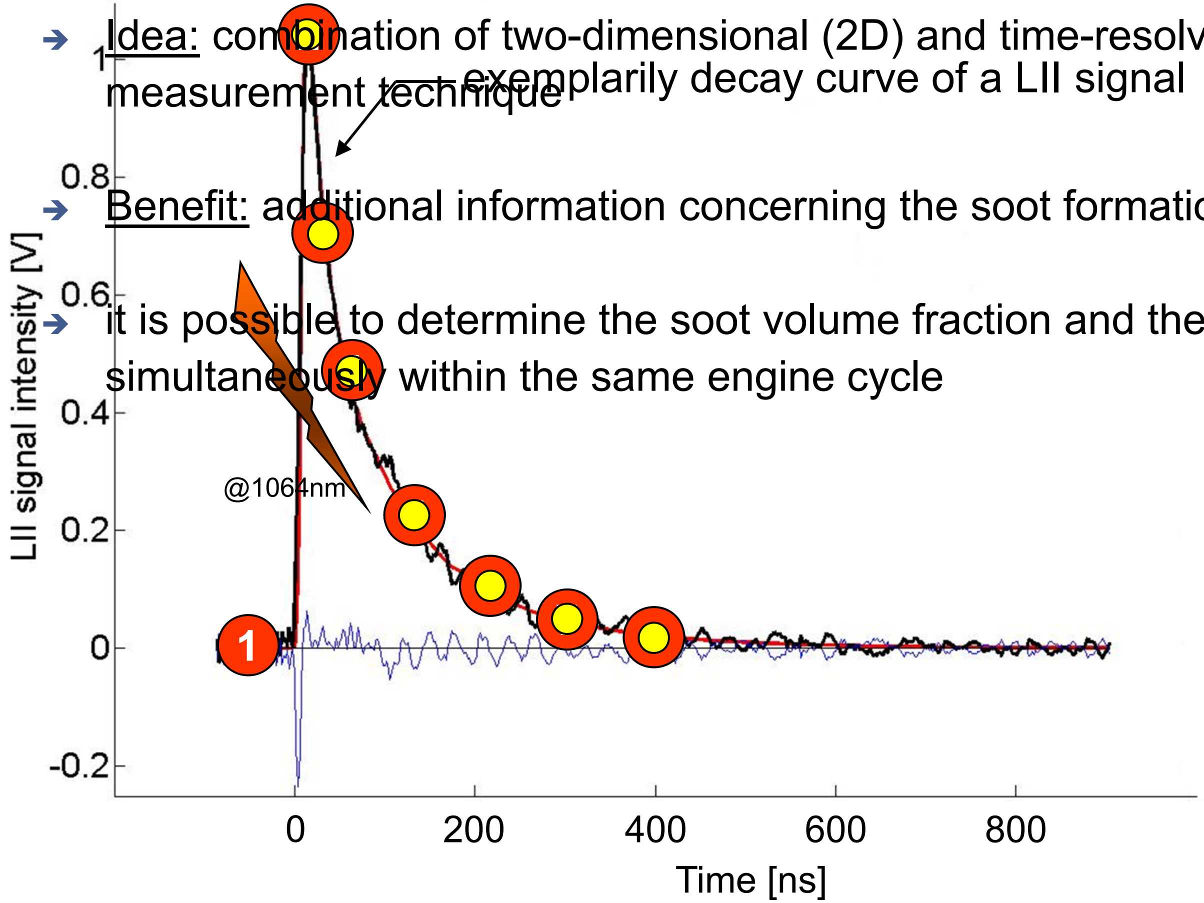
Outlook: Innovative Measurement Approach

2D Time Resolved LII:

- Idea: combination of two-dimensional (2D) and time-resolved LII to one single measurement technique
- Benefit: additional information concerning the soot formation can be achieved
- it is possible to determine the soot volume fraction and the particle sizes simultaneously within the same engine cycle



Strategy:

- recording of 8 frames within the decay curve → information about the soot volume fraction
- spot luminescence (frame 1) is subtracted from the remaining frames
- seven points to interpolate a decay curve can be defined using the intensities of each frame
- this obtained decay curve can be compared to a simulated decay curve
- determination of the particle sizes

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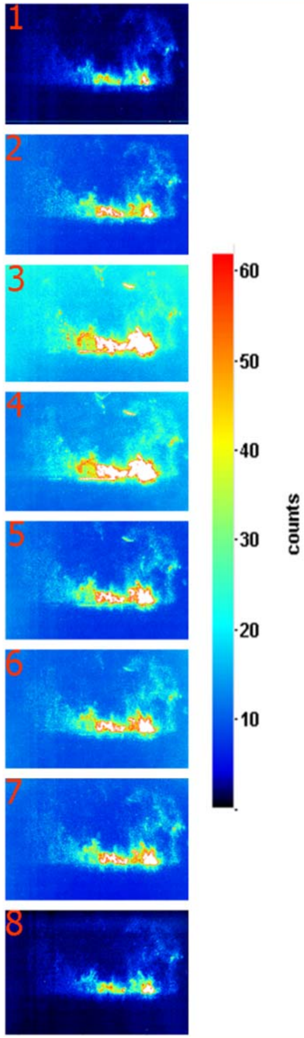
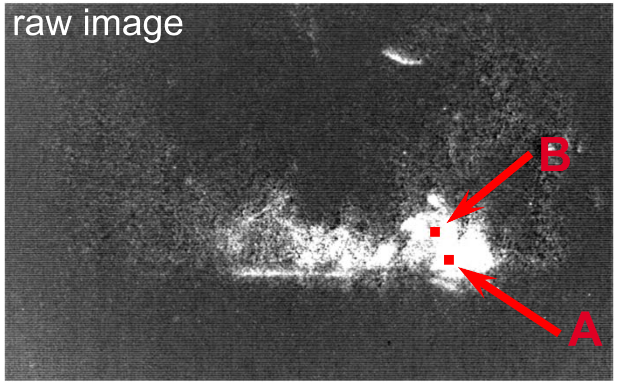
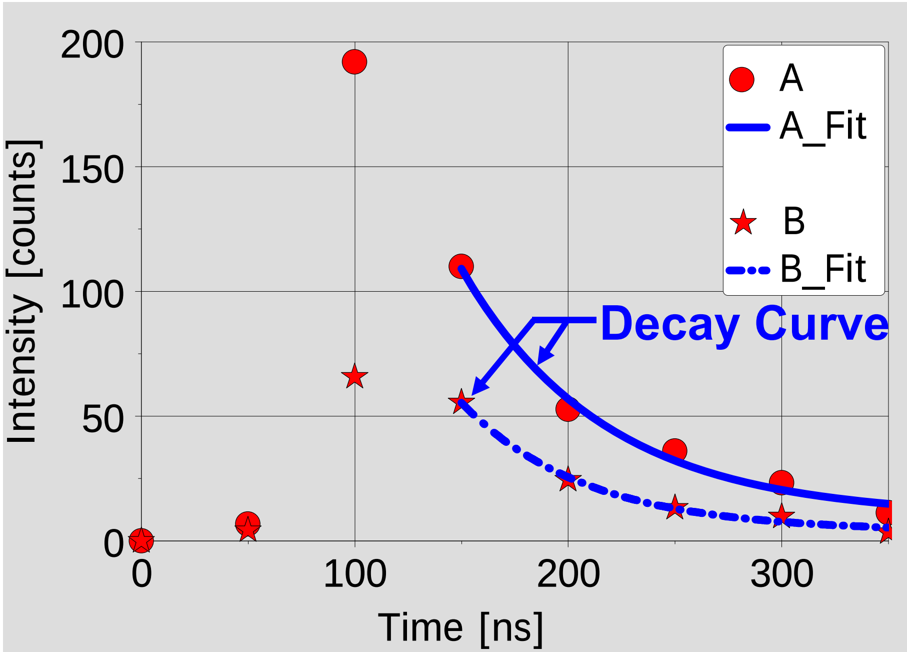
Outlook: Innovative Measurement Approach





used Decay Function:

$$y = a_0 + a_1 * \exp(-a_2 x)$$



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=
damping coefficient

hed1sh; 30.05.2011

Summary

- ➔ different particle measurement techniques have been established successfully in combination with an optically accessible gasoline direct injection engine
- ➔ studies include systematic variations of engine and injection parameters
- ➔ a new measurement approach could be identified (2D Time Resolved LII)
- ➔ main soot sources: wetting of the piston, the cylinder walls and the inlet valves, as well as insufficient homogenization
- ➔ the specific contribution of each soot source depends strongly on the operating point and the injector type
- ➔ injection pressure, injection timing and the shape of the spray have to be adjusted to the geometry of the combustion chamber, the inlet valve timing and the charge motion
- ➔ already very small variations have a significant influence on the particulate emission

Thank you for your attention.