

# Spatially Resolved Determination of Fuel/Air Ratio Inside a Direct Injection SI-Engine Under Real Fuel Conditions

V. Beushausen<sup>1)</sup>, T. Mueller<sup>1)</sup>, O. Thiele<sup>1)</sup>, T. Wesker<sup>1)</sup>, R. Grzeszik<sup>2)</sup>, J. Raimann<sup>2)</sup>, S. Arndt<sup>2)</sup>

<sup>1)</sup>Laser-Laboratorium Goettingen e.V., Hans-Adolf-Krebs-Weg 1, D-37077Goettingen, Germany, Phone: +49 551 5035 23, e-mail: [Volker.Beushausen@llg.gwdg.de](mailto:Volker.Beushausen@llg.gwdg.de)

<sup>2)</sup> Robert Bosch GmbH, FV/SLE2-Sh, PF 106050, D-70049 Stuttgart, Germany

The present work describes a new method which allows the spatially resolved quantitative determination of gaseous hydrocarbon densities in droplet laden flows. The technique is especially dedicated to a quantitative and linearly spatially resolved measurement of air/fuel ratio ( $\lambda$ -value) in direct injection Otto engines under stratified operation and by use of regular gasoline (Euro Super). The new method is based on spontaneous Raman scattering. It is applied to the investigation of the air/fuel ratio distribution inside and in the close surroundings of the spray cone of different DI-fuel injectors under stratified and homogeneous engine operation conditions. Both crank angle resolved snap shot and cyclical averaged measurements are presented. Simultaneously the planar gasoline distribution is detected by LIF of aromatic hydrocarbons which are native constituents of regular gasoline. It is shown, that the linear spatially resolved air/fuel distributions measured by means of LIF correlate well with the Raman data.

## 1. Introduction

Quantitative determination of air/fuel ratio ( $\lambda$ -value) inside gasoline SI-engines by means of spontaneous Raman scattering is generally carried out with ultraviolet laser radiation due to the stronger Raman cross sections in the UV-spectral range [1,2]. The application of UV-light determines the use of none fluorescing and therefore aromatic hydrocarbon free model fuels, so that real engine conditions cannot be realized. Additionally the development of direct injection combustion processes complicates the application of spontaneous Raman scattering for  $\lambda$ -value determination due to the simultaneous appearance of gaseous fuel and fuel droplets in the measurement volume. On the one hand the Raman signal originating from the liquid phase falsifies the measured  $\lambda$ -value, which is defined by the ratio of air and *gaseous* fuel only. On the other hand additional interfering effects occur, when high laser power densities interact with small transparent droplets. First, the droplets focus the laser light, which strongly increases the local power density. This frequently generates air breakdown resulting in very bright broadband atomic emissions, which strongly interfere with the weak vibrational Raman signals of the molecules. Secondly, the spherical shape of the droplets causes the appearance of morphology dependent resonances (MDRs) [3,4], leading to a non-linear rise of the Raman signal.

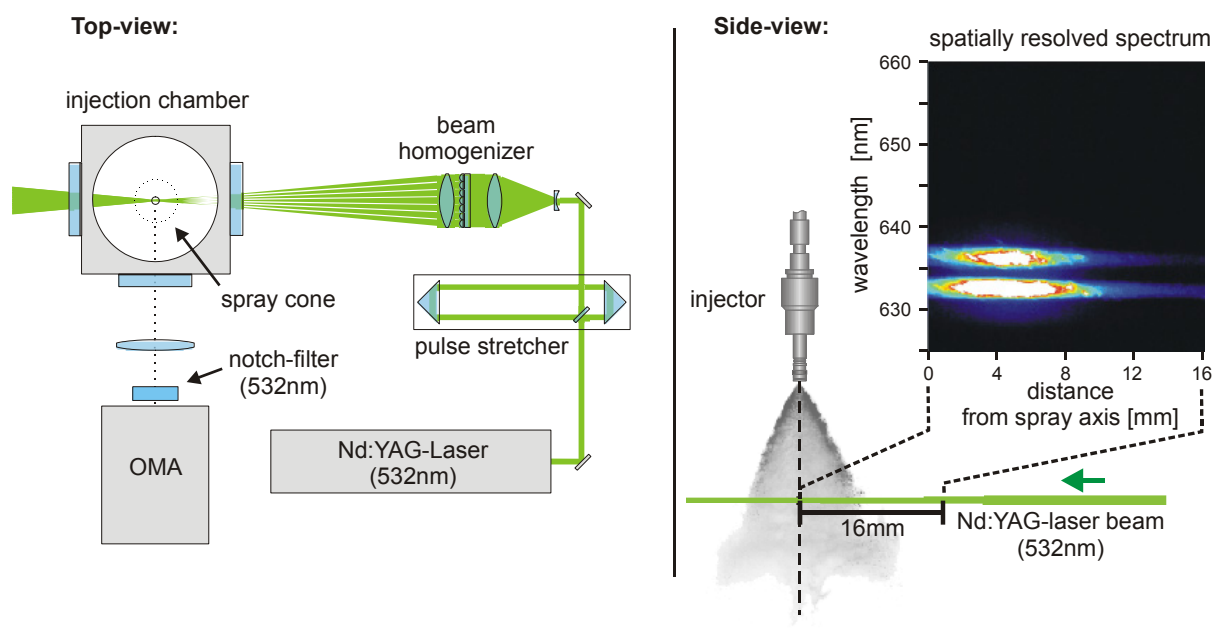
For these reasons the quantitative determination of  $\lambda$ -value by means of UV-Raman-scattering inside the cylinder of Direct Injection (DI)-engines is only possible on two conditions: a) Use of non fluorescing model fuels and b) existence of a droplet free

measurement volume. The first restriction implies, that realistic mixture formation as it appears with regular gasoline is very difficult to simulate with model fuels like isooctane. The second restriction results from the fact, that a quantitative measurement of  $\lambda$ -value will be strongly aggravated due to interference from plasma emissions and excessive Raman-scattering intensities from the liquid phase. Due to the fact that the appearance of droplets in the measurement volume is hardly avoidable, a correct spatially resolved determination of air/fuel ratio in stratified engine operation is nearly impossible with previous methods. The present work describes a new approach which overcomes these limitations and permits a spatially resolved measurement of the  $\lambda$ -value in droplet laden gas flows and the application of regular gasoline (Euro Super). Just like the previous methods the technique presented is also based on spontaneous Raman scattering. In order to avoid interference from fluorescence of aromatic hydrocarbons visible laser radiation (second harmonic Nd:YAG: 532 nm) is used. The investigations are carried out in a single cylinder DI-glass ring engine (AVL) in close cooperation with Robert Bosch GmbH.

## 2. Preliminary tests

In order to separate the Raman emissions of gaseous and liquid gasoline and to determine the  $\lambda$ -value in the droplet laden flow following principle is applied: A dye is dissolved in the gasoline which strongly absorbs the green frequency doubled Nd:YAG-laser light and re-emits the absorbed energy in a spectral region where it does not interfere with the desired Raman lines of oxygen, nitrogen and hydrocarbons. The dye concentration is chosen such that the excitation light is already absorbed by the dye in a very thin outer spherical layer of the droplets so that only minor Raman emissions from the droplet will occur. Applying this principle a selective detection of Raman scattering from gaseous gasoline should be possible. The capability of this procedure is checked by means of a technique developed by Mueller et al. [5]. This technique makes use of the special properties of alkanols whose vibrational OH-Raman emission in the liquid phase is spectrally shifted to shorter wavelengths compared to the gaseous phase. This is due to hydrogen bonding in liquid alkanols which slightly shifts the molecular energy levels. With this technique it is possible to spectrally separate liquid and gaseous gasoline so that the feasibility of the proposed method for suppressing Raman signals from liquid gasoline can be evaluated. Since the method of Mueller et al. relies on the existence of OH-groups in the molecules (e.g. alkanols and water) these preliminary investigations are carried out using methanol as the fluid.

The preliminary experiments are carried out in an optically accessible injection chamber where a methanol spray is generated by means of a Bosch BDI-injector (see fig. 1). The focused beam of a frequency doubled Nd:YAG-laser (LOT, Brilliant B, 50 mJ) was coupled in perpendicular to the spray axis and the generated Raman scattered laser light is detected by an optical multichannel analyzer (OMA) consisting of a spatially resolving spectrograph (Acton Research Corporation, Spectra Pro 300i) and an intensified CCD-Camera (LaVision, Flamestar 3). In order to avoid droplet induced gas breakdown the very short Nd:YAG-laser pulse (pulse length 5 ns) was stretched to 20 ns pulse length by a homebuilt pulse stretcher consisting of delay line and beam splitter. This task reduced air breakdown significantly but still single breakdown events could be observed which could falsify the measurements. For this reason additionally a beam homogenizer consisting of a beam expander, two crossed cylindrical lens arrays and a focusing lens was utilized in order to avoid hot spots in the beam profile. The homogenizer creates a tall homogeneous beam waist with 1.5 mm diameter in the

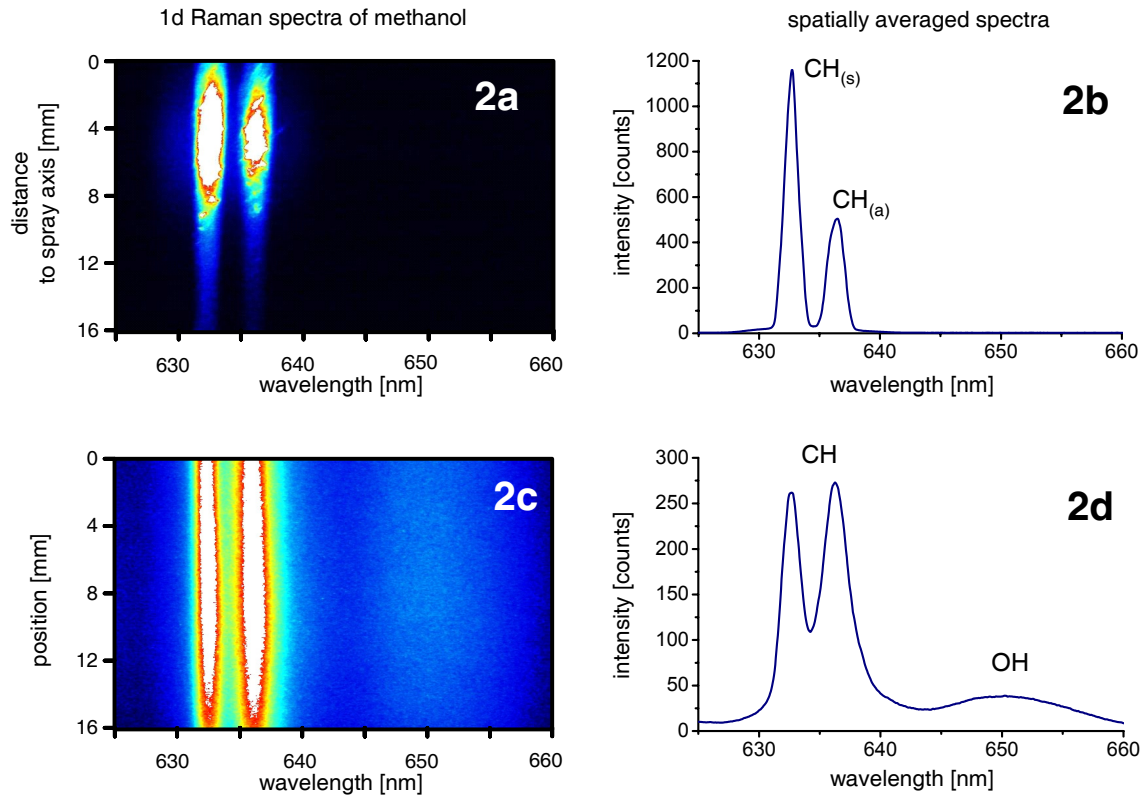


**Fig. 1:** Experimental setup for preliminary tests

measurement volume. A 16 mm long part of the homogeneous laser beam inside the spray and approx. 6 mm below the injector tip was imaged onto the slit of the spectrograph by a single lens.

Fig. 1 (side view) and fig. 2a show a spatially resolved Raman-spectrum of the methanol spray which is generated in this way during the experiments. Light intensities are color coded and no calibration procedures are applied in order to account for variations in light intensity, transmission losses and camera sensitivity. In the wavelength range 630-640 nm the symmetric and anti-symmetric CH-stretching vibration is clearly visible. Furthermore it is recognizable that these emissions appear mainly in a spatial region approx. 5 mm apart from the spray axis. This is due to the hollow cone structure of the spray and represents the intersection of the laser beam with the spray cone where a multitude of small methanol droplets are present. Fig. 2b shows the according spatially averaged spectrum which is derived from Fig. 2a by digital averaging the counts of all spatial positions in dependence on the wavelength. It has to be highlighted, that the Raman line of the OH-stretching vibration, which is an inherent feature of the methanol spectrum and should appear around 650 nm, is not detectable in the spray!

In liquid methanol which predominantly is available in the measurement volume 6 mm below the injector a Raman spectrum would have been anticipated as is shown in fig. 2c and 2d. This spectrum is attained in bulk methanol with the same experimental setup but much higher camera gain. For constant temperature and presumed that only linear Raman scattering adds to the signal, the intensity ratio of OH- and CH-stretch vibration is a molecular constant of methanol. This leads to the only conclusion that in the spray cone in fact also Raman emissions of the OH-vibration occur, but the CH-emissions arising from droplets are orders of magnitudes stronger, so that the high dynamic range of the slow scan CCD-camera (12 bit) is not sufficient to permit simultaneous detection of CH- and OH-Raman emissions. Such excessively strong selective super elevation of the CH-Raman scattering intensity can only be explained by the occurrence of stimulated Raman scattering in the spray droplets: It is known from literature that transparent micro spheres act as tiny laser resonators [4,5]. Incident as well as Raman scattered photons perform several round trips inside the droplets due to total

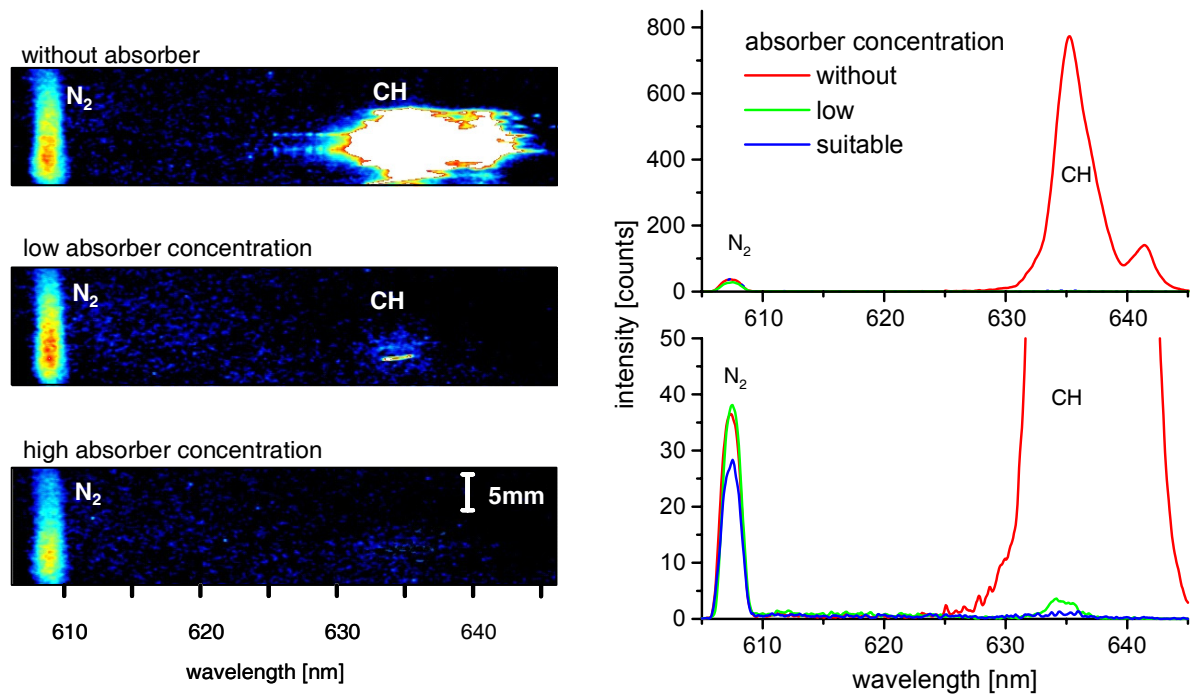


**Fig. 2:** Methanol Raman-spectra. a) spatially resolved spectrum of a methanol spray, b) spatially averaged spectrum of a methanol spray, c) spatially resolved spectrum of bulk methanol, d) spatially averaged spectrum of bulk methanol

reflections at the air/liquid interface. Phase matching at the laser wavelength strongly increases the strength of the incident electric field inside the droplets, leading to an increase of generated Raman photons. For field strengths higher than a certain threshold stimulated Raman scattering occurs, especially when the described input resonance coincides with an output resonance at the wavelength of the Raman photons. Since stimulated Raman scattering in contrast to spontaneous Raman scattering is a nonlinear process, the signal intensity strongly depends on laser energy in a nonlinear way and of course on the droplets morphology. By investigating the influence of varying laser energy on the intensity ratio of CH- to  $N_2$ -Raman lines it could be verified that in fact the extreme super elevation of the CH-emissions in the droplets can be traced back to stimulated Raman scattering.

In order to enable gas phase Raman signal extraction in droplet laden flows it is therefore indispensable to effectively suppress these unexpectedly strong stimulated scattering effects. This can be done in two ways: a) decreasing the laser energy – which in turn leads to an unacceptable decrease of the anyway weak Raman signals, b) decreasing the cavity quality so that the threshold for stimulated effects can no longer be reached with common laser powers. In order to reduce the stimulated emissions out of the spray option b) is realized. For this purpose the gasoline which is used as the spray fluid is doped with a none evaporating dye (sudan red), which effectively absorbs the laser photons incident on the droplets and shows no fluorescence that could interfere with the Raman emissions.

Fig. 3 shows the influence of the absorber concentration in gasoline (Euro Super) on the intensity of stimulated Raman emissions from droplets. In the left part of the figure spatially resolved Raman spectra from the spray cone averaged over 100 laser shots are displayed. In



**Fig. 3:** Influence of absorber concentration on CH-Raman emission intensity

order to reduce read out noise the camera was operated in the line binning mode: 8 CCD-lines respectively are combined to one single super line. Top down the absorber concentration in the gasoline was increased successively. The highest absorber concentration displayed in the lower row of Fig. 3 was about 1g/l. The  $N_2$ -Raman line is recognizable at 608 nm and the Raman emissions of the gasoline CH-stretch vibration occurs in-between 630-650 nm. The broadening of the CH-line is due to simultaneous emission of numerous different hydrocarbon species which all exhibit a slightly different bond strength. Especially the Raman emission band ranging from 640 nm to 644 nm can be allocated to CH-stretch vibrations of aromatic hydrocarbons. The intensity of the emissions is color coded. In order to enable better comparison, these spectra are displayed again spatially averaged and with different scaling in the right part of the figure.

It is noticeable that extremely strong stimulated CH-Raman emissions occur when no absorbing dye is present in the droplets. The detected CH-emissions are approx. 30 times stronger than the simultaneously recorded  $N_2$ -emissions (upper spectrum). Furthermore the strong decrease of the CH-emission intensity with increasing absorber concentration is eye catching. During these early experiments the absorber concentration is not yet quantified – corresponding more precise investigations of this effect are in preparation. With the lower Raman spectrum it could be demonstrated effectively that not only *stimulated* Raman emissions could be suppressed almost completely, but also the *spontaneous* Raman emissions from droplets which interfere with the desired Raman signals from the gas phase are no longer detectable.

This result shows effectively that the addition of a non evaporating absorber to the gasoline enables the determination of gas phase gasoline concentrations almost unaffected by droplet emissions. It was possible to suppress the stimulated emissions nearly completely. The fact that in this case no Raman emissions from gaseous gasoline were detectable is based on the fact that under these experimental conditions (no preheating, detection volume spatially close to the injector tip) at the time of detection no vaporization has yet taken place.

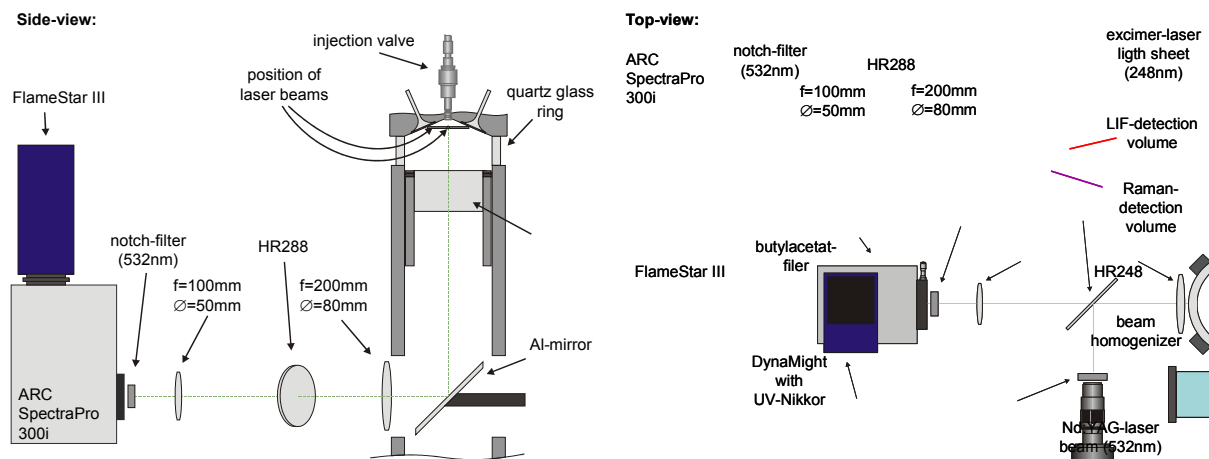
As a further important result it should be noted that in contrast to Raman investigations with UV-laser light the application of visible laser radiation (532 nm) avoids completely the unintentional creation of interference from aromatic hydrocarbon fluorescence

### 3. Engine investigations

First applications of the described technique under real engine conditions were carried out in a Bosch research engine with direct gasoline injection (AVL-single cylinder glass ring engine). Apart from the transparent cylinder wall an additional optical access was provided by a big piston window ( $\varnothing=60$  mm). The experimental setup is displayed in Fig. 4. In order to prevent destruction of the quartz ring and gas breakdown in the combustion chamber due to high energy densities in the laser beam, the frequency doubled Nd:YAG-laser pulse was temporally stretched by a pulse stretcher and eliminated from hot spots by the beam homogenizer mentioned above. This modified laser beam was coupled into the cylinder perpendicular to the cylinder axis. It was focused at a point on the cylinder axis 10 mm below the centrally positioned injector tip. The laser induced emissions were coupled out through the piston window and were detected by the optical multi channel analyzer (OMA) described above. In order to suppress Mie-, Rayleigh and surface scattered light a holographic notch filter centered around 532 nm was positioned in front of the OMA.

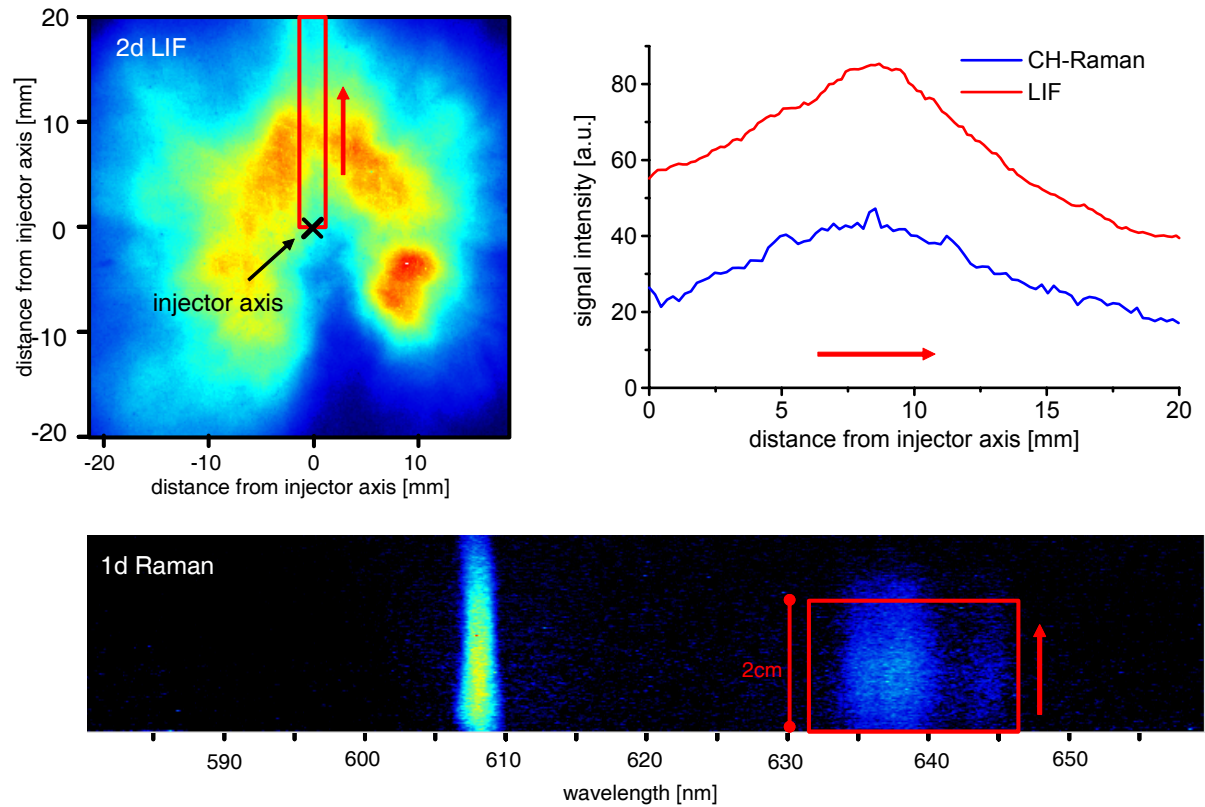
Simultaneously a KrF-excimer laser light sheet was generated in the cylinder on the same level than the focused Nd:YAG-Laser beam in order to simultaneously visualize the planar gasoline distribution by means of aromatic hydrocarbon fluorescence. The fluorescence images were detected through the piston window by a slow scan CCD-camera (Dynamight, 16 bit, LaVision GmbH). Interference from elastically scattered 248 nm laser light was completely suppressed by means of a 1 cm thick butylacetat filter. Unintended detection of elastically scattered Nd:YAG-laser light could be avoided by firing both lasers a couple of nanoseconds after another. The synchronization of engine and Nd:YAG laser was facilitated applying a YEX-module (LaVision GmbH). As the fuel Euro-Super gasoline was used, this was doped with the absorber dye.

A typical result detected with this experimental setup is shown in Fig. 5. The displayed distributions (uncorrected raw data) were attained at 18 CA btdc and are averaged over 100 engine cycles. In the upper left the planar distribution of Euro Super at a level 1 cm below the injector tip is represented. Imaged is an area of 40 x 40 mm with the injector in the center.



**Fig. 4:** Experimental setup at the transparent engine





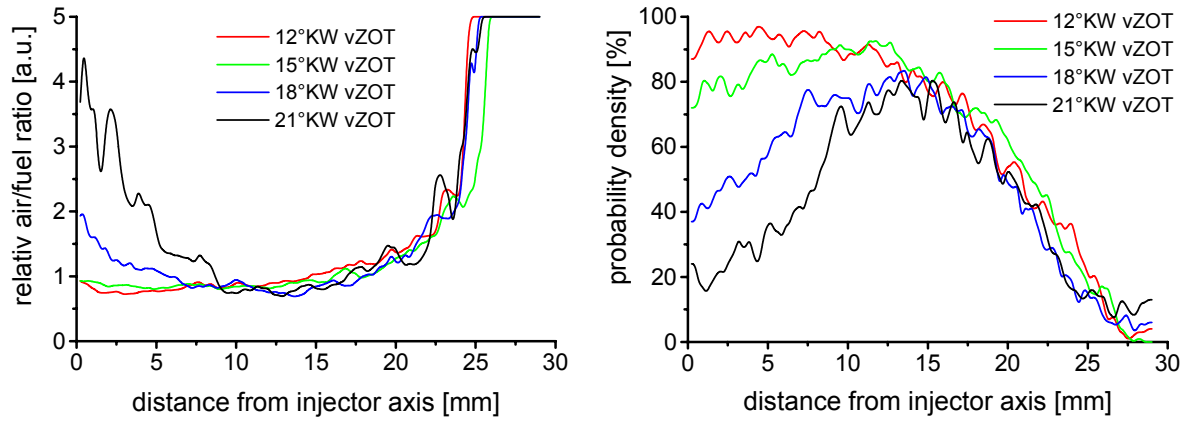
**Fig. 5:** Simultaneously detected planar gasoline fluorescence distribution and one dimensional spatially resolved Raman spectrum as well as the comparison of LIF and Raman intensities

The rectangle inscribed in the image marks the measurement volume of the Raman investigations. The intensity profile averaged in this rectangle along the short edge is displayed in the right part of the figure. The bottom part of the figure represents the simultaneously detected Raman spectrum.

As already discussed for the results of the cell experiments in Fig. 3 the  $N_2$ -Raman line at 608nm and the strongly broadened CH-band in-between 630-650 nm is clearly detectable under engine running conditions. Although during detection at 18°CA fuel droplets are still present in the measurement volume there is no evidence for their existence in the spectrum (no stimulated emissions, no gas breakdown). The spatial extension of the inserted rectangle matches exactly the length of the LIF-profile in the graph above. By averaging over the spectral axis a spatial profile of the CH-Raman intensity (= relative gaseous fuel density) along the measurement volume is achieved. This Raman intensity profile and the corresponding LIF profile are opposed in the right part of the figure.

The good correlation of the intensity profiles extracted by the different measurement techniques is conspicuous. This leads to the assumption that due to the absorbing dye in the fuel under the present conditions also the LIF-signal does not include any excessive contribution from droplets where the molecular density of the fluorescing hydrocarbons is orders of magnitude higher than in the gas phase. More precise investigations concerning this topic are presently under investigation.

Apart from the determination of the relative fuel density based on the CH-Raman intensity also quantitative spatially resolved  $\lambda$ -values can be extracted from the Raman data by generating the ratio of  $N_2$ - and CH-Raman intensity and calibration of this relative  $\lambda$  with a known  $\lambda$ -value distribution. Since the engine is not fired during the experiments the use of  $N_2$ -intensity instead of  $O_2$ -intensity is allowed. In this experiment the calibration step is not



**Fig. 6:** Spatially resolved relative air/fuel ratio and probability density for gasoline appearance at 4 different crank angles for a multi hole injector.

yet carried out, so that only relative spatially resolved  $\lambda$ -values for different crank angles are calculated from the Raman data. In Fig. 6 examples of relative spatially resolved  $\lambda$ -values for 4 different crank angles 1 cm below a multihole injector tip are displayed. Clearly detectable is the decrease of the air/fuel ratio in the axial spray region with decreasing crank angle. Additionally it is clearly visible that in a radial distance of approx. 25 mm from the spray axis the  $\lambda$ -value increases strongly for every crank angle.

Apart from the cyclic averaged investigation illustrated above also snap shot images of the relative fuel density distribution for different crank angles were accomplished. By means of a threshold consideration the probability density of the fuel along the linear measurement volume was determined (see Fig. 6). This type of data evaluation enables insight into cyclic fluctuating quantities and delivers important information for the correct positioning of the spark plug and the stability of the ignition process in direct injection Otto engines.

#### 4. Conclusion

The present work describes a new method which enables a spatially resolved quantitative measurement of the air/fuel ratio in droplet laden flows and by use of regular gasoline (Euro Super). The technique presented is based on the detection of spontaneous Raman scattering. In order to avoid interference from fluorescence emissions of aromatic hydrocarbons visible laser radiation (532 nm) is applied. It is shown, that occurring stimulated as well as spontaneous Raman emissions from fuel droplets can be suppressed effectively by decreasing the droplet resonator quality at the wavelength of the incident laser light. This technique is applied to a direct injection Otto transparent engine where for the first time interference free  $\lambda$ -values could be measured in the droplet laden flow of the regular gasoline spray. Cyclical and crank angle resolved quantitative investigations of the instantaneous gaseous gasoline distribution are accomplished which for the first time enables realistic evaluation of the spatial and temporal fluctuation behavior of the gaseous fuel density and the  $\lambda$ -value by use of regular gasoline.



## 5. References

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