HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **D2.1**

A method for measuring in-cylinder λ-distribution in medium-speed DF engines

Revision Final

Nature of the Deliverable:	Report
Due date of the Deliverable:	01.01.2016
Actual Submission Date:	21.12.2016
Dissemination Level:	Public

Contributors:

Stefan Karmann (TU Munich)

Markus Mühlthaler (TU Munich)

Dr. Maximilian Prager (TU Munich)

Prof. Dr. Georg Wachtmeister (TU Munich)

Dr. Fridolin Unfug (MAN Augsburg)

Work Package Leader Responsible: Dr. Johan Hult (MAN CPH)

Start date of Project: 01/05/2015 Duration: 36 months

Grant Agreement No: **634135-HERCULES-2**

HORIZON 2020

The EU Framework Programme for Research and Innovation

TABLE OF CONTENTS

1 Summary

Due to the Horizon 2020 program with one focus at the increasing challenge of future transportation the Hercules 2 project deals with the improvement of maritime propulsion systems. To reach that goal one part of the Hercules 2 project investigates the dual fuel combustion in large bore sized marine engines. The dual fuel combustion uses alternative fossil fuels (e.g. methane, LPG, LNG, etc.) in a lean premixed combustion process with a pilot diesel flame for ignition. By the use of a lean premixed combustion process the emissions of the normally used diffusive combustion process especially NOx and soot decrease.

To improve the combustion process efficiency the knowledge of the combustion, injection and emission has to be increased. Therefore the goal of the WP I.2.4. of the Hercules 2 project is the development of a measurement technique for in-cylinder lambda-distribution in a medium-speed dual fuel engine.

To set up such an investigation, the requirements and special demands that arise with a large bore marine dual fuel engine in comparison to a car-sized engine have to be considered like increased thermal and mechanical loads for the optical access and an increased absorption rate of the triggered laser light sheet for the measurement technique. Based on a literature review, some first concepts for optical accessibility were assembled in a CAD model. The changes in the engine design are the following. For the lateral optical access the commonly used supporting ring is divided into two new parts. For assembling three concepts of optical inserts a new intermediate ring between the cylinder liner and cylinder head with an adapted coolant duct is used. To make the upper part of the engine accessible, the cylinder liner is shortened and rearranged with a modified liner module. To guarantee the appropriate force flux the cylinder liner is mounted in the new locking plate. A main effectiveness criterion of the optical access is the observable field of view in the combustion chamber. Therefore possible lens effects are considered to increase the observable range. In addition to the lateral access a further access via the cylinder head is also possible.

An overview of already applied measurement techniques was used as a basis to discuss their applicability to measure a three dimensional λ-distribution in a large bore medium speed dual-fuel engine. In dual-fuel operation, natural gas, which consists mainly of methane, is used as fuel. The fuels' spectral properties and the wish for quantitative results deems two laser-based measurement techniques suitable - Laser Induced Fluorescence (LIF) and Raman spectroscopy. LIF in combination with tracers is able to provide species-specific results, a planar spatial distribution and a relatively high signal intensity. Raman spectroscopy on the other hand, due to its inelastic nature, provides species-specificity as well, but is limited to a 1D-extent. However, simultaneous multi-species concentrations are obtainable in one timestep.

A conceptual arrangement brought the aspects mentioned above together. 15 optical inserts provide a lateral optical access into the combustion chamber. The combination of planar LIF and Raman spectroscopy enables the cycle-averaged acquisition of the in-cylinder lambda distribution.

2 Introduction

Two third of the world's transportation is accomplished by about 45 000 ships travelling the oceans. Due to the lasting effects of globalization, the amount of ships will increase to guarantee the supply of the world's population. It is obvious that the future solution for transportation becomes more and more a challenge due to the shortage of fossil fuels and the increasing legal limitations of exhaust gas like CO_2, NOx and Sulphur. These limitations are already reality. With the upcoming IMO Tier III especially the NOx limitation becomes regulated in special areas (ECAS). The tremendous reduction of NOx emissions is shown in Figure 1. To fulfill this upcoming regulation, Troberg [1] outlined eight technical possibilities for NOx reduction and gave an overview of their potential of saving NOx emissions, [1].

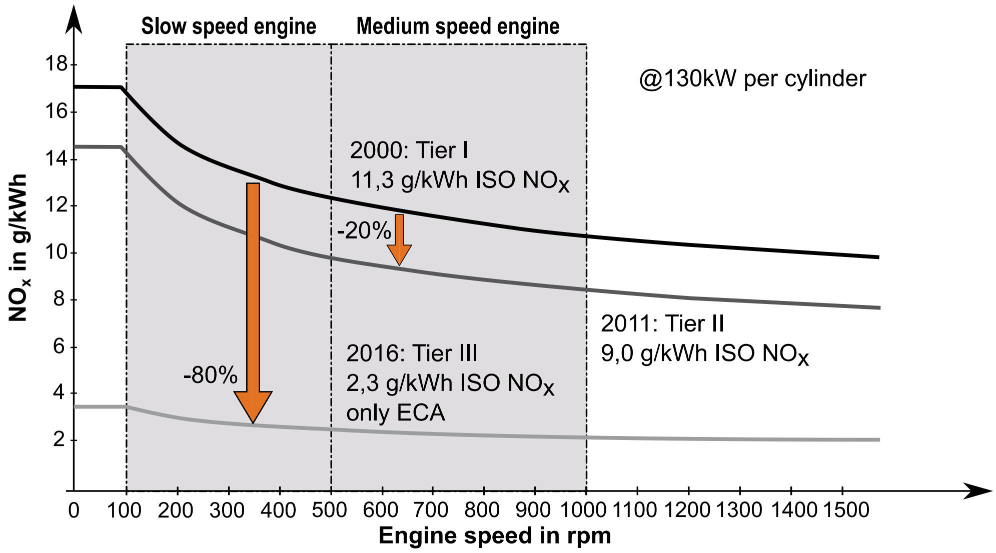

Figure 1 Development of exhaust regulation (cf. [1])

The Dual fuel engine is the only solution, which can reduce the NOx emission of about 80% and fulfill the Tier III requirements at the same time (c.f. [1]).

The challenge of the future transportation is an international issue. Therefore, already in 2004 the world's biggest maritime propulsion suppliers MAN and Wärtsilä initiated the Hercules project. With the support of the European nation the need for such a project was emphasized. With research and industry partners the Hercules Project has now been an ongoing project for ten years to increase the efficiency, reduce emissions, increase reliability and lifetime of maritime propulsion systems (cf. [2]). After these ten years with the projects Hercules A, B and C the Hercules 2 project continues the research. One task of the new Hercules 2 project is the research on multi-fuel combustion which is used in dual fuel engines to reach the strong NOx regulation requirements. To improve the technology of multi fuel combustion the knowledge of combustion, injection and emission has to be increased. Therefore, a medium speed four-stroke dual fuel single cylinder engine has to be equipped with an optical access. This access is being used to investigate the λ-distribution in the cylinder to identify abnormal combustion conditions. The possible optical accessibility of the single cylinder research engine and the measurement technique for the given task are discussed in the following sections.

3 Concept studies of optical accessibility to a medium speed four stroke engine

For more than 150 years, engineers have been interested in observing the inner workings of combustion engines during the whole working cycle and especially during the combustion process. Even the first engine by Otto had have an optical access made of a glass cylinder. The goal for having a look into an engine is to get a better understanding of the processes in the combustion chamber and improve the combustion process. With these increased knowledge it is possible to make engines more efficient concerning fuel consumption, emission production and even lifetime increase. Hence the optical measurement techniques and of course the possibilities of getting optical access to combustion engines have improved and developed tremendously.

3.1 *Requirements for optical access*

The realization of an optical accessible large bore marine dual fuel engine causes further challenges for the optical diagnostic and for the design compared to passenger car or truck sized engines. These much smaller sized engines are already optically investigated to a high amount and variation. The investigation at a large bore medium speed dual fuel engine subjects to higher thermal and mechanical loads by higher in cylinder pressure and increased vibrations. To be able to develop a design in the following section it is necessary to specify the terms of condition for the optical accessible medium speed fired four stroke dual fuel engine.

The first and most important requirement is to direct light in and out of the combustion chamber. Therefore, it is required to use light transmittable materials for a wide range of wavelengths suitable for the investigated effects (cf. Section 4). Furthermore, it is not sufficient if only a very small range of the combustion chamber is observable. Therefore, one criteria for the efficiency of an optical access is the observable area. This area has to be suitable concerning the investigated phenomena. According to this main requirement only a few materials are suitable (glass materials). In comparison to the usually used material (steel) the transmittable materials offer different properties as shown in Table 1.

Material	**Coefficient of thermal expansion.** [1/K]	**Heat conductivity** [W/mK]	**Tensile strength** [MPa]	**Compressive strength** [MPa]
Quartz glass	$0{,}54 \cdot 10^{-6}$	$1{,}38$	50	1150
Sapphire glass	$6{,}2 \cdot 10^{-6}$	42	190	2000
Steel[1]	$12 \cdot 10^{-6}$	$40 - 60$	$310 - 630$	250 - 1200

Table 1 Comparison of optical and non optical material properties

The second requirement is the comparability of the optical engine to the all metal engine. According to the material properties it is obvious that there are differences between an engine with glass parts and an all metal engine. These differences are:

- Thermal behavior due to the changed heat conductivity
- Mechanic stability due to thermic stress and reduced tensile strength
- Operating time due to the fouling of the glass surface caused by combustion arrears (soot, formaldehyde) until no light is transmittable

It is obvious that these differences increase in proportion to the amount of glass parts which are used in the engine to increase the spatial resolution of the combustion chamber. As to passenger car sized engines comparisons between a full optical engine and an all metal engine can be found in [3] and [4].
Concerning these differences the following requirements for the design have been derived to fit the operating behavior of the optical engine close to the all-metal engine:

- Increased/ adapted cooling to fit the engine operating temperature and operating time
- Appropriate glass design to the type of duty
- Easy accessible optical ports for cleaning

[1] According to the great variety of steel only a small range is considered as an example.

Of course there is a tradeoff between the maximization of the observable area in the combustion chamber and the comparability due to the material specification of the optical parts. This tradeoff is also considered in Subsection 3.3 and in respect to this only a compromise of realistic engine behavior (full load conditions) and maximum observable field of view in the combustion chamber is possible and realizable.

3.2 Classification of optical accessible combustion engines

In this section the overall possibilities of optical accessible engines will be described and the reasons for the chosen concept focus are exposed.

As mentioned before due to the long history of combustion engines and the ambition for ongoing improvements a great variety of optical accessible engines has been developed. A collocation can be found in Table 2. It is obvious that the majority of these optical accessible engines are of passenger car or truck sized type. Only a clear amount of medium speed or low speed engines with optical accessibility are published and built. Hereby the elaborations of Hult and Wellander are to emphasize, [5], [6]. Nevertheless it is possible to deduce three general concepts of optical accessibility (cf. [7]). Based on this classification the concepts suitable for the planned medium speed engine were developed. These concepts are shown in Figure 2 Comparison of concepts for optical accessibilityas principle schemes. The concepts are classified according to their degree of optical accessibility. From concept one: **Minimal Invasive** to concept four: **Maximal Invasive** the observable field of view in the combustion chamber increases. Simultaneously due to an increased amount of optical elements the comparability of the optical engine and the all metal engine decreases (cf. [4]). Hereby not only the optical components (especially the glass parts itself) are responsible for the loss in comparability. There are also design changes needed e.g. the adaption of the cylinder head, piston and - depending on the concept - the crank mechanism which leads to altered geometric conditions (e.g. a decreased compression ratio). Furthermore the changed border conditions due to the endurable thermic and mechanic load of the glass parts prevent an identical engine behavior, so that a limited engine runtime and even a skipped fired engine run is necessary to prevent serious damage to the engine and the optical components.

Engine size Bore x Stroke [mm]	**Applied Measurement Technique**	**Optical access**	**Source**
320/440 four stroke	Flame emission	I	Unfug, [8]
340/430 four stroke	LIF flame propagation	II	Wellander, [6]
340/400 four stroke	High speed flame propagation	II	Duong, [9]
320/400 four stroke	Fuel jet breakup, chemiluminescence	I	Disch [10]
500/2200 two stroke	Fuel jet ignition, In cylinder flow	III	Mayer, Hult [5,11,12]
170/210 four stroke	High speed flame propagation	IV	Korb, [13]
Passenger car sized engine			
84/90 four stroke	OH LIF flame propagation	I	Bensing, [7]
75/88,3 four stroke	PIV	IV	Jakob, [14]
79,5/95,9 four stroke	LIF, Raman spectroscopy	IV	Greis, [15]

Table 2 Overview conducted optical engines and carried out measurements

With concept I: **Minimal Invasive** the lowest impact of the engine can be achieved. This concept is an excellent possibility for a full series or close to series engines. The concept uses endoscopic access via the cylinder head and/or glass fibers. Glass fibers can be fitted in almost every part of the engine (cylinder head [16], spark plug [17], etc.) and several commercial systems are already available. The main disadvantage of this concept is the limitation of the observable field of view and the spatial resolution.

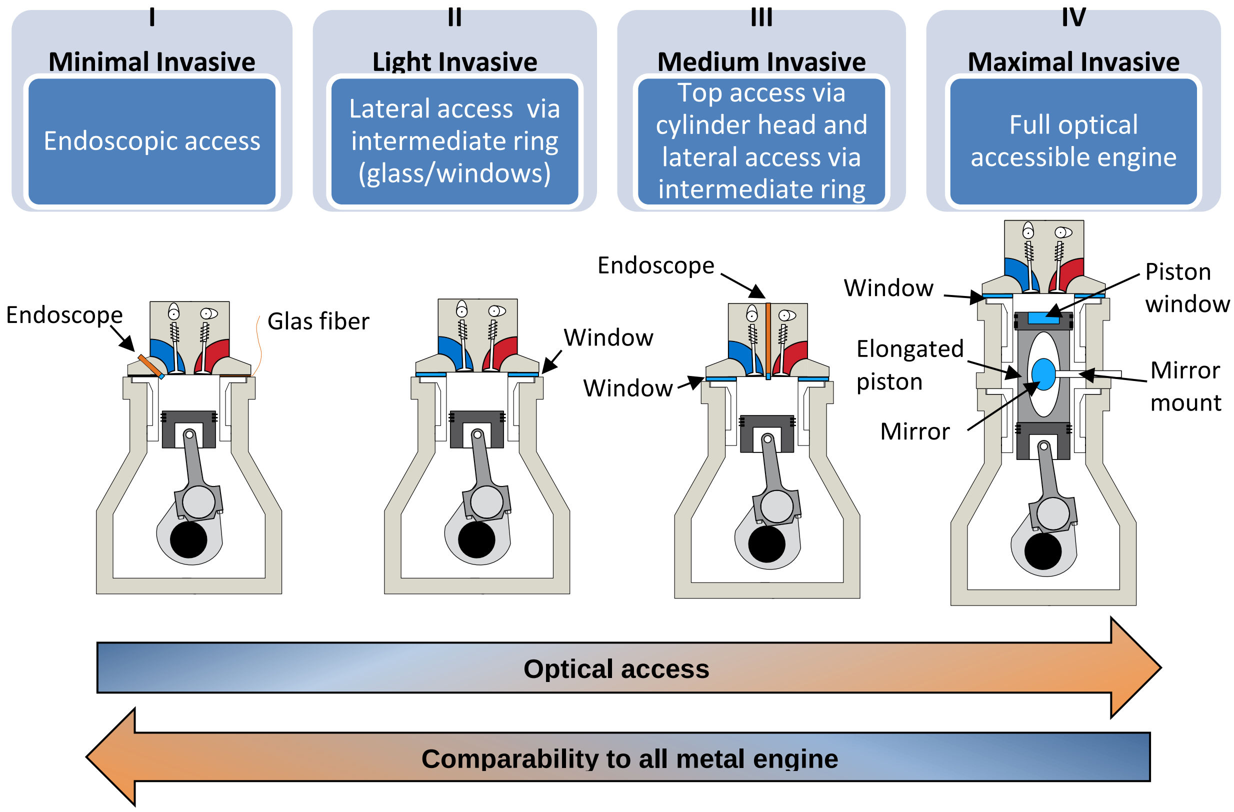

Figure 2 Comparison of concepts for optical accessibility

The concept II: **Light Invasive** uses an intermediate optical part between the cylinder head and cylinder liner. This intermediate part can be realized in three different ways. One possibility is the design as a glass ring like it is described in [7]. The second way to include an optical intermediate part is to use a steel ring fitted with windows that are mainly made of quartz glass like it is done in [18] or [6]. The two designs mostly differ regarding the window design. In [6], a curved window is used for exploiting the optical effects to increase the observable field of view whereas [18] describes a flat window. The third design is done by Mayer and Hult, [5,11,12]. For a large two stroke diesel engine an optical cover was developed with several ports where the optical inserts can be mounted. Beside the increased observable field of view, an increased flexibility for laser-based diagnostics is achievable. The main disadvantage of this concept is the limited view into the cylinder bowl and the reduced field of view when the piston covers the optical intermediate part in top dead center.

To overcome the disadvantage of concept II: **Light Invasive** and increase the observable field of view in the combustion chamber the concept III: **Medium Invasive** combines the easy endoscopic access of concept I: **Minimal Invasive** with the intermediate ring of concept II: **Light Invasive**. Realized endoscopic access to a large bore marine diesel engine can be found in [19] and [8].

The last concept shows the deepest impact at the engine due to the highest design changes. The main advantage of this concept is its degree of optical accessibility. Concept IV: **Maximal Invasive** uses an elongated piston with an optical piston crown and a stationary mirror to look into the combustion chamber or to excite the species in the combustion chamber via laser light. In addition an optical intermediate ring is used for the lateral access. This concept according to Bowditch [20] was realized in [13].

A pre-decision for the concept of the optical access was possible according to the requirements depicted in Subsection 3.1 and further aspects were considered:

- **Optics** like quality of measurement data resolution, optical distortion, transmission, possible maximum laser energy
- **Understanding** concerning the possibilities of investigating the combustion, in cylinder flow and pilot fuel injection can be investigated (flexibility of measurement techniques)
- **Cost** including the complexity, reliability risk and effort of the design
- **Comparability** of the generated measurement data to the all metal engine

In respect to these considerations and estimations the focus was set to concept III and IV. After a detailed investigation of concept IV with regard to the mechanic stability, it was obvious that this optical access is not suitable for the planned medium speed four stroke engine. Hence the concept according to Bowditch was neglected and the emphasis was set to concept III.

3.3 Optical accessibility: Concepts for lateral access

The main advantage of concept III in a design perspective is the diversion of the lateral and top view access. For the lateral access the concept shown in figure 3 has been developed.

The whole concept is based on the replacement of the original supporting ring. Instead of the supporting ring, two new parts are installed: The **Intermediate ring** and the **locking plate**. The concept is shown in Figure 3. The intermediate ring houses the optical inserts from concept 3a to 3c. In addition the cooling duct is integrated. The integration of the new intermediate ring necessitates the displacement and modification of the cylinder liner. Furthermore two sealing points are necessary and the modification of the cylinder head. To increase the installing space for the intermediate ring the piston has also to be modified. The locking plate houses the cylinder liner and integrates a further coolant duct for the upper part of the cylinder liner. A third coolant duct (not shown in the picture) for the cylinder head is fed from the intermediate ring. Each coolant duct is fed individually, allowing an individual temperature for the cylinder head, the intermediate ring and the upper part of the cylinder liner to be adjusted. Beside the new intermediate ring and locking plate, original series parts (cylinder head, piston, cylinder liner, crank train) can be used or are modified to build up the optical accessible engine.

The optical inserts (**concept 3a, concept 3b** and **concept 3c**) can be mounted in an appropriate modified intermediate ring. According to the three different possibilities of realization the different concepts uses a curved glass at the combustion chamber side (Concept 3a), flat small sapphire inserts (Concept 3b) and flat wide glass windows (Concept 3c). According to Figure 3 the additional dead volume due to the position of the inserts and amount of them increases from concept 3a to concept 3c. Concept 3a offers the best mechanic and thermic stability due to the amount of windows, the small heated glass surface close to the combustion chamber and the dimension of the windows. Also the observable field of view due to the use of optical effects via the glass curvature is maximal for concept 3a. For concept 3b the observable field of view is minimal. According to the dimensions of the optical insert concept 3c offers a much larger field of view then concept 3b and is almost close to concept 3a. All concepts have a perpendicular arrangement of the optical inserts in common.

The main aim which was pursued by developing the concepts is to design a flexible and reliable optical access with a maximum observable field of view.

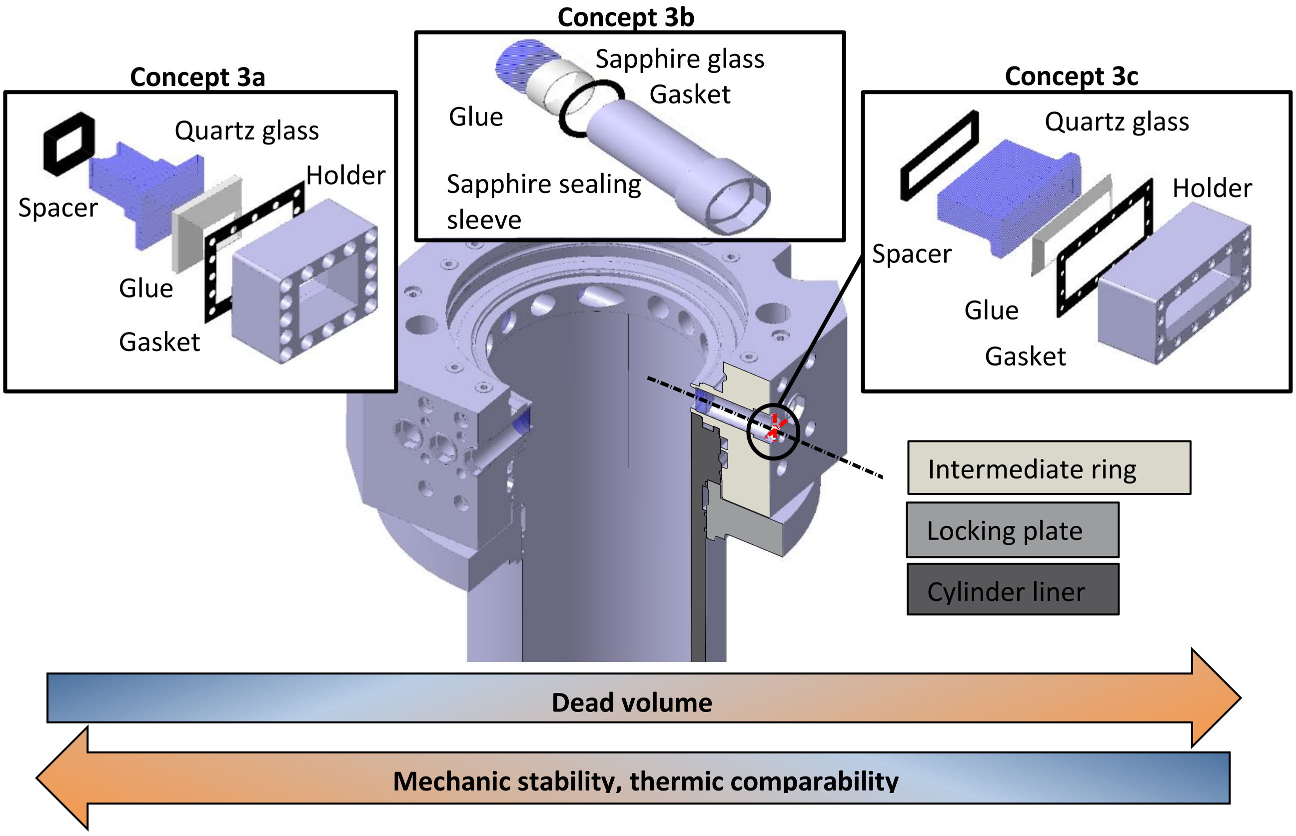

Figure 3 Concept for lateral access

3.4 *Optical accessibility: Concepts for top view access*

In contrast to the easy top view access of Mayer and Hult for a two stroke marine diesel engine with only one central exhaust valve in the cylinder head, a four stroke engine with two inlet and two exhaust valves does not offer too much unused installing space in the cylinder head, [5,11,12]. Therefore, an obvious possibility for the dual fuel engine mode is to replace the main injector with an endoscopic access. With this access, a centered view from the top into the combustion chamber and especially into the piston bowl is possible.

An additional access can be established by omitting an exhaust valve. This possibility was used in [8] where during the casting process the casting core for one exhaust valve was omitted. This provides an opportunity to add an additional optical access to the cylinder head. Of course depending on the engine layout the leave out of an exhaust valve alters the in cylinder flow conditions. This has to be compensated by changes of the appropriate inlet and exhaust conditions at the test rig.

The adaption of an additional access in the cylinder head serves as an increase of the visual ascertainable range in combination with the lateral access.

3.5 *Optical accessibility: Concepts for visual range optimization*

After the illustration of possible positioning, form and size of the individual optical inserts, the next step focuses on possibilities to increase the achievable field of view. As a result, ideally the whole compression volume should be covered. Practically this will become a challenge.
The glass itself can either be flat on both sides, use a curvature on the side facing the combustion chamber or the environment or even be curved on both sides.

A concave curvature at the combustion chamber facing side acts as a diverging lens, thus increasing the numerical aperture and therefore the collection angle. If the curvature is added as depicted in Figure 3, the window collects a greater angle inside the chamber than a window of the same width with a flat surface. The test rig from Wellander and Duong used windows of that kind, [9,21].

The collection angle can be further increased if the curvature is stronger than dictated by the bore diameter. However, in this case additional dead volume is introduced. Another aspect in this trade-off is the introduction of optical aberrations due to the lens. The image quality has to be carefully evaluated.

4 Concept studies of a measurement method for in-cylinder lambda-distribution

An optimized optical access enables a field of view that covers most of the bore diameter as well as the compression volume around top dead center. This fulfills the condition to record the in-cylinder lambda distribution shortly before the ignition throughout the inflammation and combustion. To quantify the air-to-fuel ratio, the fuel's concentration needs to be measured. For this task, an overview of previously applied techniques is given and a solution, which accounts for the special circumstances due to the bore size and natural gas as fuel, is developed.

4.1 Literature overview about optical measurement techniques at large bore engines

The following overview focuses on measurements carried out at the engine itself, thus disregarding specialized test rigs, Table 2. Unfug investigated the spectrally unfiltered flame emission as well as the fuel jet penetration length on a four-stroke diesel engine of comparable size, [8,8]. The engine was accessed by borescopes and the Mie-scattered light recorded in a cycle-resolved manner. Disch compared different pre-chamber designs in a natural gas engine by acquiring jet propagation and breakup via OH* chemiluminescence through an endoscopic access, [10].

What all these approaches have in common is their specific design for one measurement task. Mayer and Hult designed a more flexible two-stroke diesel test rig, which is more comparable to the well-known fully optical accessible engine. The initial flame ignition process was investigated through high-speed visualization of the flame emission and temperature measurements by two-color pyrometry, [12]. The arrangement of the 24 windows covers an increased percentage of the combustion volume, thus enabling velocimetry by double pulse laser-sheet imaging, fuel jet penetration and spray angle measurements via Mie scattering, [5].

Fully optically accessible engines offer the unparalleled detection of a plane perpendicular to the cylinder axis. Korb gathered data on cycle-resolved radial flame propagation, [13]. Numerous experiments were undertaken on truck sized test rigs, collecting single-cycle-resolved, 3D-distributed imaging of fuel and OH-concentration with the use of a high-repetition-rate laser cluster, [22–24]. Planar laser sheets are spatially distributed by rapidly changing their position, thus providing a measurement volume. Kaminski combined planar laser induced fluorescence (PLIF) of OH and fuel with the tracers 3-pentanone and acetone quasi-simultaneously with a similar laser cluster, [25]. Wellander pushed the application of PLIF measurements to a lean burn large bore pre-chamber gas engine with lateral access via windows, [6]. He obtained data about the early flame development and used acetone as a fuel tracer to visualize the fuel distribution. Besides he focused on diagnostics development of time resolved 3D imaging of OH PLIF in a flame and the measurement of the local extinction coefficient in a dense spray.

Along with the number of test rigs, the previous applications available in the literature decrease with an increase of the bore diameter. To the authors' knowledge, no literature exists on a fully optically accessible large bore engine.

4.2 In-cylinder lambda-distribution measurement

As stated before, in order to obtain the in-cylinder lambda distribution the measurement of the fuel's concentration is required. Concentration measurements can be made by a number of techniques – conventional and laser-based.

Laser based techniques offer in-situ measurements with high resolution, both spatial and temporal, thus being perfectly suited for concentration measurements. They are non-intrusive when compared to traditional methods like gas sampling probes, [26,27].
The detection of intermediate species such as OH yields specific information about the flame front propagation. The ability to capture multiple species-specific measurements simultaneously in a quantitative manner minimizes measurement time whilst providing additional information, [28,29].
Laser imaging is widely used in combustion diagnostics over various stages of optical engine accessibility.

Experimental considerations

The detection of the whole combustion volume in one frame is unlikely. Even if it were granted by the optical access and with several cameras in position to record simultaneously, the excitation might still be the limiting factor. To do so, the laser beam would not only have to be stretched to a planar sheet, but into the third dimension, thus further decreasing the energy density. Also, the illumination of a volume loses the spatial exactness of a laser sheet with a typical thickness of less than one mm. In this case the mapping is more comparable to the integral nature of a line-of-sight method, which limits the local discretization.
It is important to consider what phases are to be measured. For port fuel injection and natural gas as fuel, the gaseous phase provides information about the main fuel. The liquid phase is of interest when the interaction of the diesel pilot jet with the flow is taken into account.
The measurement of the local distribution of the air-to-fuel-ratio can either rely on the detection of the fuel concentration alone or specifically take a measured oxygen concentration into consideration. In the first case, the air-to-fuel-ratio is derived by assuming uniform distribution of air in the cylinder. However, the presence of residual gas, exhaust gas recirculation or mixture inhomogeneity impose errors, [30].

Suitable laser-based techniques

In principal, two laser diagnostic techniques fulfill the requirements. Laser induced fluorescence (LIF) in combination with tracers provides species-specific results, a planar spatial distribution and a relatively high signal intensity. Relative data is easily obtained, absolute measurements on the other hand require careful calibration and consideration of perturbations.
Raman spectroscopy, due to its inelastic nature, provides species-specificity, but is usually limited to a 1D-extent. However, simultaneous multi-species absolute concentrations are obtainable in one timestep. The applicability compared to LIF is more difficult, because the anticipated signal level is several orders of magnitude smaller. In between lies the signal level of Rayleigh scattering. The principle of elastic scattering is the technique's biggest weakness, as it leads to species-unspecific scattered light of the same wavelength as used for excitation. It is therefore disregarded. [30,31].

Planar Laser Induced Fluorescence

The principle of laser induced fluorescence has been applied to measure species concentrations, temperature, pressure and velocity in flames, [26]. After excitation of the probe volume by laser radiation, the resulting spontaneous emission from molecules or atoms is the detected measurement signal. Daily reviewed the physical background and application possibilities in detail, [32].

In order to excite a molecule absorption at the desired laser wavelength is required. The use of pulsed Nd:YAG lasers is common, with a first harmonic at 1064 nm, that can be doubled to 532 nm, tripled to 355 nm or even quadrupled to 266 nm, as they are readily available and provide sufficient pulse energies. Another popular source of laser radiation are excimer lasers, e.g. KrF-lasers that emit at 248 nm. As natural gas consists mainly of methane, we regard it equal to fuel. Figure 4 shows the spectral absorption intensity of methane on an arbitrary scale. Ponderable values are only reached in the near to mid infrared and the deep ultraviolet spectrum, thus methane itself cannot be excited with readily available laser sources, [31]. In theory HeNe-lasers operating at 3.39 µm fulfill the wavelength criterion, but lack the required energy due to their continuous mode of operation. Eichler lists the difference between the averaged powers of Nd:YAG- and HeNe-lasers with about three orders of magnitude, [33].

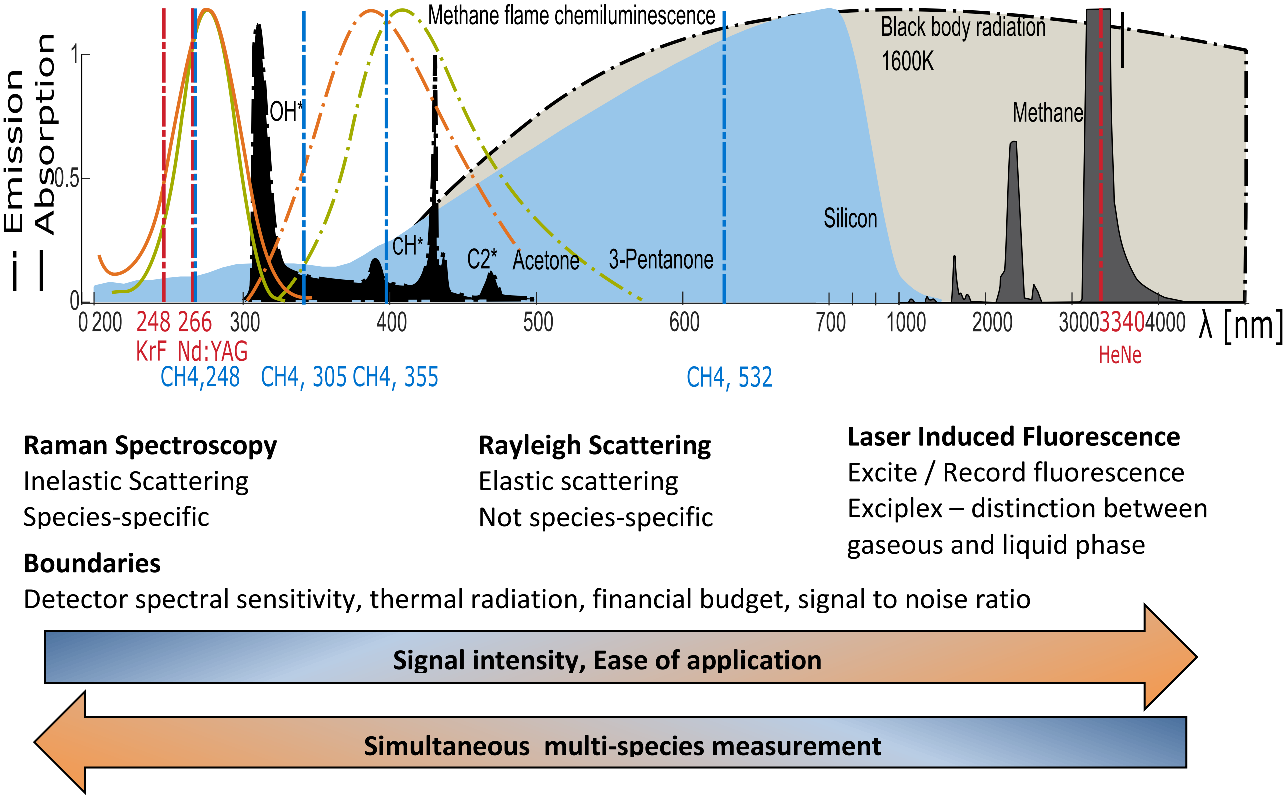

Figure 4 - Emission and Absorption of different materials in regard to measurement applicability.

However, tracer substances seeded to the fuel circumvent the missing fluorescence. According to Schulz they should fulfill the following requirements, [28,29]:

- Behave exactly like the measurand, e.g. fuel (Reaction rate, reactivity, evaporation, droplet formation, convection, diffusion)
- LIF signal intensity shows direct proportionality to the desired quantity
- No influence because of ambient conditions

Practically, a dependence on local temperature, pressure and bath gas compensation is observed and investigated, [28].

Especially when absolute concentrations are desired, a high effort for calibration and in-depth knowledge of the tracers spectral response shift caused by varying ambient conditions is necessary. For widely used tracers studies already provide this data under the application of pressure, temperature and ideally the combination of both, e.g. [34,35]. Calibration can also be carried out by imaging once in motored operation, thus producing comparable environmental conditions and the injection of a reference gas of known composition. After that, the actual measurement is undertaken in fired operation, [36].

Whenever absolute values are to be obtained another obstacle has to be overcome. Fluorescence quenching, which is extinction through collisions, diminishes and eventually removes the fluorescence signal beyond the lower detection limit.
A direct fuel-to-air-ratio measurement approach, named FARLIF, assumes that quenching through oxygen is the dominant reason for de-excitation, e.g. with toluene as a tracer [37]. The neglect of intramolecular de-excitation leads to a proportionality between excited molecular states to the tracer and oxygen number density. However, more recent studies concluded this assumption to be false for pressures and temperatures present in internal combustion engines, [38–40].

Frieden and Koban applied the tracers toluene and 3-pentanone simultaneously in a spark-ignited direct-injection engine, [41,42]. The fuel concentration was measured by toluene, the oxygen concentration determined by the signal ratio of the two tracers, thus giving the air-to-fuel-ratio.
Tracer systems able to form an *exci*ted com*plex* (exciplex) allow the simultaneous detection and distinction of the liquid and gaseous phase.
Kazenwadel investigated the usability of an already present odor marker in natural gas – Tetrahydrothiophene (THT) - which emits the need for fuel-tracer-mixture generation. The fluorescence intensity showed a linear inverse proportionality to the air-to-fuel ratio in an industrial burner. The applicability is limited as the absorption is only noteworthy below 250 nm and therefore accessible e.g. by excimer lasers. [43].

Table 3 shows an excerpt of previously applied tracers in natural gas combustion processes. Publications with a focus on tracer characterization are also included, even though they were acquired in gasoline or diesel engines.

Substance	**Vapor Pressure [mbar, 293K]**	**Spectral position [nm]**		**References**
		Absorption	**Emission**	
Acetone	246	220-340	310-490	[6,21,22,25,35,44,45]
Toluene	29	230-280	270-320	[28,35,38–40,40,41,46,47]
3-pentanone	16	220-340	330-580	[25,35,39,41,44,47,48]
Triethylamine (TEA)	67.7	220-280	270-350	[45,48,49]
Trimethylamine (TMA)	1859	248*	270-320	[49,50], * = Defined excitation, no spectrally resolved data.
Tetrahydrothiophene (THT)	19.3	210-250	260-320	[28,43]
Anisole	3.6	240-290	270-360	[35,51]

Table 3 - Some previously applied tracers in natural gas combustion processes, including publications with a focus on tracer characterization.

The fluorescence signal is proportional to the tracer's absorption cross section, the fluorescence quantum yield and the number density, which in the gaseous phase is depending on the vapor pressure. Quenching also influences the fluorescence quantum yield. These values are not constant, but vary with e.g. pressure, temperature and laser excitation wavelength. In order to account for this complicated correlation, the expected environmental conditions have to be closely considered. [30].

A two-dimensional image plane is attained through sheet optics. In the simplest setup a spherical lens collimates the beam and is followed by a cylindrical lens. The cylindrical lens expands the laser beam along one axis and forms a thin sheet with thicknesses generally below 1 mm.

Raman Spectroscopy

Raman scattering is an inelastic process - when a photon collides with a molecule, a change in the rotational and vibrational energy levels occurs and energy is transferred. A laser generates photons for the interaction and can lift a molecule to a higher energy level, thus emitting a photon of lower energy. The emitted photon loses energy and is therefore shifted to a higher wavelength by a discrete, species-specific quantum with a linear proportionality to number density. This process emits scattered light, whose bands are called Stokes lines. Due to the relatively high signal yield, we limit ourselves to this case.

The discrete shift makes simultaneous detection of multiple species like for example O_2 and CH_4 possible, thus predestining its application for air-to-fuel ratio measurement. Zhao and Eckbreth describe the physical background and successful applications in detail, [30,31].

Raman spectroscopy is not affected by residual gas or exhaust gas recirculation, as it determines the air-to-fuel ratio directly, unlike LIF that is solely based on fuel concentration. Another advantage over LIF is the proportional increase of Raman scattering intensity towards higher pressures, [44]. This enhances the applicable engine operating points.

Species	**Vibrational frequency [cm^-1]**	**Spectral position of Q-branch Stokes line [nm]**			**Vibrational cross-sections [x 10^-30 cm^2/sr]**		
		248 nm	**355 nm**	**532 nm**	**248 nm**	**355 nm**	**532 nm**
N2	2331	263.2	387.0	607.3	13.0	2.79	0.46
O2	1388	256.8	373.4	574.4	16.6	3.69	0.65
	1285	256.1	371.9	571.0	11.1	2.49	0.45
CH4	2915	267.3	396.0	629.6	80.2	16.6	2.61
	3017	268.0	397.6	633.7	53.7	11.1	1.72

Table 4 - Characteristic vibrational frequencies and Raman cross-sections of some species of interest to IC engines at room temperature, [30].

The Stokes lines of some species of interest to internal combustion engines are given in Table 4. The vibrational cross-section has a frequency scaling to the fourth power, it increases for shorter laser wavelengths. The output Raman signal does not increase with the same factor, caused by a decrease of photons per laser pulse at the same time. Due to the low signal level, the technique suffers from background radiation and scattered light. Because the Raman signal is spectrally separated, the interfering noise can effectively be minimized by optical filters. The polarized nature of vibrational Raman scattering can be used to suppress broadband interference of OH and O2 by vertical polarization and detection of the laser pulse. [30,31].

In order to achieve a sufficient signal-to-noise-ratio, the technique is usually limited to one-dimensional collection. However, in combination with a two-dimensional method like PLIF, a pointwise calibration for absolute measurements is possible, [52]. Richter applied the combination on an internal combustion engine with promising results, [44].

Optical and electrical signal detection

The matter of detection is both relevant for LIF and Raman measurements with only slight differences. To improve the signal-to-noise ratio, both the optic and the electric signal detection and multiplication is subject to optimization. Signal decrease due to optical loss cannot be reclaimed. Considerable effort lies in the selection of optical materials for windows or guiding lenses with superior transmission properties from 260 nm up to the visible range. Sapphire, fused silica, CaF_2 and MgF_2 are a few examples of suitable materials. Surface reflections are kept at a minimum through multi-layer coatings, designed for the desired wavelength window.

For the optoelectrical signal transformation, monochrome cameras based on CMOS- or CCD-chips are generally preferred, as they offer higher detail and sensitivity, [53]. At a given active area per pixel, only one instead of three individual detectors is needed. Most conventional cameras are based on Silicon semiconductors. Silicon absorption decreases towards the ultraviolet region, which directly lowers the responsitivity given in Ampere per Watt and limits the measurement to about 200 nm. The limit for long wavelengths is around 1100 nm. In combination with an image intensifier the lower limit is bypassed, on the cost of added noise and decreased spatial resolution.

Ideally, the measurement should take place in a spectral area with no background radiation interfering with the signal. In reality, this theoretical signal to noise ratio cannot be reached. The hot gases in the combustion chamber can be modeled as a black body radiator. A contribution of broadband interference diminishes the ratio from the visible up to the infrared spectral region, which is added in Figure 4 for a conservatively estimated temperature of 1600 K. For higher temperatures, the lower emission limit is shifted to shorter wavelengths. The broadband chemiluminescence emission of a methane flame, highlighted in black, is another source of noise. Generally, shorter wavelengths are not as heavily polluted but add other deficiencies. The decrease of spectral response in the ultraviolet region for silicon semiconductors requires image intensification for minority species detection.

Whereas for LIF the recording is carried out by a camera and optionally an image intensifier, Raman spectroscopy requires a spectral decomposition to identify distinct species-specific signal peaks. Therefore, an imaging spectrometer is necessary to get a 1D-measurement.

4.3 Challenges due to large bore size

Studies on large bore engines of comparable size noted effects that limited the recorded optical quality as well as the spatial resolution more apparent than in passenger or truck sized engines, [6] [21]. Wellander reported signal fluctuations caused by variations of the spatial energy profile as a result of density gradients in a fuel jet. These gradients led to a variation of refractive indexes, both affecting the scattered light as well as the excitation source, thus overlaying a blur to the recorded images. Sharper data was recorded for small path lengths through the dense fuel jet. [6].

The increased diameter results in greater distances between the excited area of interest and the detector. Along that distance, signal attenuation due to absorption originating from the hot and pressurized gas environment needs to be considered.

Curved windows that follow the contour of the cylinder require correction optics in order to depict a planar image plane. As the windows don't cover the whole bore diameter, lens effects due to a curved inner side lead to a higher numerical aperture and may be used to cover a bigger area.

To minimize the measurement time, the desire to image over the whole diameter at once is present. If granted by the optical access, the excitation via the laser sheet needs to provide a reasonable thickness along the axis over this distance. Too much variation in thickness can lead to insufficient energy densities. Optimized designs circumvent this limitation by keeping the thickness at an acceptable level over longer distances, [54].

Engine vibrations have to be taken into consideration because of the proximity of sensitive measurement equipment, especially of image intensifiers. Preliminary tests should quantify the expected vibrations and might require the use of ruggedized hardware.

4.4 Expandability and additional measurement appliances

Highlighted in black is the broadband flame chemiluminescence emitted by a methane flame. Both the emission of the radicals OH* and C_2* is spectrally narrow and shows a distinct peak, which is suitable for detection via image intensifiers. The literature cites OH*-chemiluminescence as an indicator for the flame front, [26]. Spectral separation to broadband interferences is achieved with an optical bandpass filter centered at 308 nm. In combination with an image intensifier and a high-speed CMOS camera, the setup enables cycle-resolved recordings.
By recording the cycle-resolved flame emission, flame propagation is visualized. This is made possible by the broadband chemiluminescence over the visual spectrum.
With a dye laser, the output laser wavelength can be fine-tuned to high precision. In that way, not only broadband excitation of tracers is possible, but narrow excitation of molecule transitions of intermediate species. Examples for previously reported measurements are OH*-3D-PLIF, excited at 283 nm or HCHO-PLIF. [55–57].
Spray diagnostics via Mie scattering or particle image velocimetry (PIV) are thinkable and could increase the understanding of fuel jet interaction and the in-cylinder flow field, along with its influence on the lambda distribution. For PIV, the flow is seeded with tracers and two images are recorded with a slight delay. In post-processing, a cross-correlation of individual particles is calculated over both images. The result is a vector field representing the velocity. The latter was already applied to a large bore engine by [8], although only at a component test rig so far.

High-speed, cycle-resolved measurements over three dimensions were applied under atmospheric conditions, e.g. [56,58–60]. With further increase in laser technology and available pulse energies of kilohertz-capable systems, their exertion in internal combustion engines is foreseeable.

4.5 Achievable quality of measurement

The temporal and the spatial resolution are connected for three-dimensional measurements. As described earlier, the transfer from planar to volumetric data is usually done by recording multiple, slightly shifted planes.

Cycle-resolved LIF measurements in an engine require laser repetition rates in the kilohertz regime. Such systems are commercially available, however they suffer from up to three orders of magnitude lower pulse energies in comparison to low-speed systems. To provide sufficient pulse energies, another approach is to build a cluster of high-power low-speed systems that operate with a slight time delay as reported by Lund University, e.g. [22]. The cluster made it possible to record up to eight planar images in rapid succession, but the recording of a whole combustion cycle with a timestep of one crank-angle was not viable. A scanning mirror was used for the repositioning of the laser sheets at an adequate timescale. The monetary expense of a comparable system is beyond the project’s budget.
Therefore the data will be collected with one frame per cycle with a frequency of up to 20 Hertz and averaged over 50 to 100 cycles for each measurement plane.

A quasi-three-dimensional volume is generated with a variable discretization along the thickness. The distance between the planes limits the spatial resolution and directly influences the required measurement time. Electronically controlled linear guidings provide the spatial distribution of the individual planes. The maximal spatial resolution is given by the guidings minimal displacement, which is in the magnitude of a few micrometers.

5 Conclusion

The efficiency of the combustion process can only be improved with thorough knowledge of the combustion, injection and emission formation. One part of this progress is the ability to measure the in-cylinder lambda-distribution in a medium-speed dual-fuel engine.
To obtain the air-to-fuel ratio within the combustion chamber, the test rig needs an optical access. On a large bore engine, considerably higher thermal and mechanical loads on top of the increased size compared to a car-sized engine are present. Based on a literature review we evaluated concepts and derived promising variants.

Figure 6 shows a conceptual arrangement that takes the covered aspects into consideration. 15 inserts, radially distributed in between the tension rods, enable the lateral optical access. The inserts' alignment is not necessarily tangential to the bore. Through an angular shift, the margin area towards the bore diameter may be better resolved.
The windows are curved on the side facing the combustion chamber in order to maximize the achievable field of view. The curvature introduces an angular deflection of the laser-sheet, so detection is not carried out perpendicular to excitation. This results in a local variation of the spatial resolution as reported by Wellander, [6].

To facilitate excitation and detection, matching pairs of inserts are always arranged perpendicular to each other. This arrangement grants fluorescence signal detection perpendicular to the collimated laser source, e.g. a laser sheet, thus achieving a finer spatial resolution, [32].
The combined application of tracer PLIF and pointwise Raman spectroscopy results in an absolute, sheet-wise detection of the air-to-fuel ratio. PLIF measurements collect relative data over a two-dimensional plane. The excitation laser-sheet and Raman detection volume are overlaid at one point, at which absolute calibration data is achieved.
The individual two-dimensional planes are generated by averaging over a sufficient number of operating cycles. The distribution of these planes by linear guidings results in quasi-three-dimensional data.
In postprocessing, considerable efforts are undertaken to combine first all images along one spatial measurement plane followed by the reconstruction of a volume.

A frequency-quadrupled Nd:YAG-laser generates radiation at 266 nm, as the ultraviolet spectral area suffers the least from background radiation. If the laser-sheet has to be collimated afterwards and reflected back into the engine for a sufficient Raman signal yield, preliminary tests have to show. Detection is achieved by a combination of image intensifier and high-speed camera to fulfill the requirements for cycle-resolved data acquisition. Optical filters attenuate background noise and scattered light interferences to improve the signal-to-noise ratio.
In order to record a specific crank-angle position within a cycle, synchronization to the engine's revolution are necessary. As a operation frequency of 10 Hz already is synchronous to one crank-angle degree per working-cycle at 1200 rpm, the double Pulse Nd:YAG's 20 Hz are sufficient. For lower engine revolutions, not every working-cycle can be recorded, thus increasing measurement time.

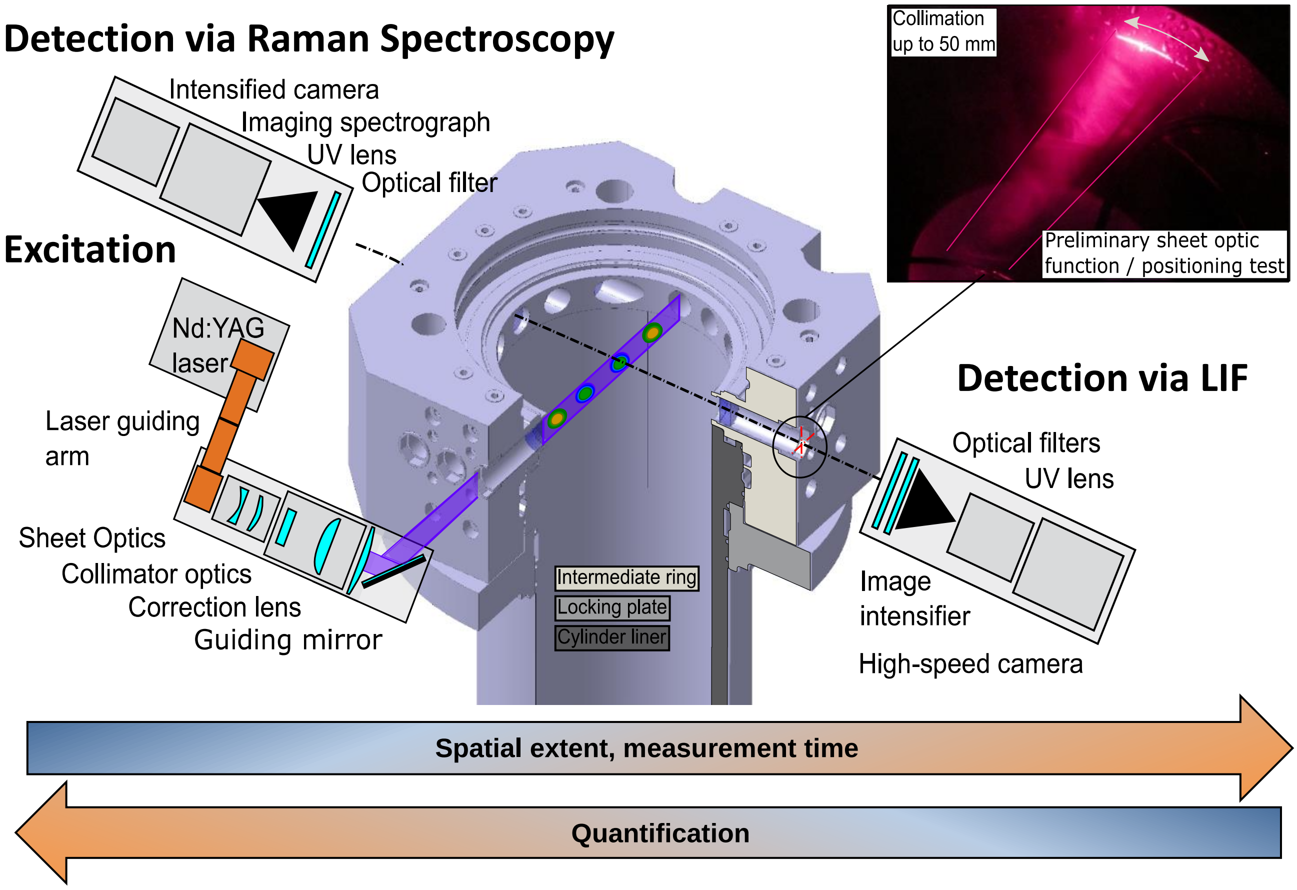

Figure 6 - Sectional view of the intermediate optical ring overlaid with a conceptual arrangement of measurement devices

Further steps

After the concept decision, the design for the lateral access will be finalized. The design will include numerical strength test analysis to safeguard against mechanical failure.

In the meantime, preliminary tests regarding the quality and spatial extent of sheet optic illumination, seeding of tracers, excitation and fluorescence behavior to find a suitable tracer and influence of the fluorescence yield over varying pressure are carried out. A measurement campaign at a truck-sized test rig will provide verification of the detection method.

Also, the integration of additional measurement techniques will be evaluated. Investigations of novel alternatives to enable a full optical access at a large bore engine will be conducted during the procurement.

6 Acknowledgment

This work has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 634135.

7 References

[1] M. Troberg, D. Delneri, in: *MTZ - Motorentechnische Zeitschrift*, vol. 71, pp. 394–401.

[2] Nikolaos Kyrtatos, Lars Hellberg, Christian Poensgen (Eds.), *Ten Years After: Results from the Major Programme HERCULES A-B-C on Marine Engine R&D*, CONSEIL INTERNATIONAL DES MACHINES A COMBUSTION, Shanghai, 2013.

[3] J.T. Kashdan, B. Thirouard, *SAE Int. J. Engines* 2 (1) (2009) 1857–1872.

[4] W.F. Colban, D. Kim, P.C. Miles, S. Oh, R. Opat, R. Krieger, D.E. Foster, R.P. Durrett, A. Manuel, D. Gonzalez, *SAE Int. J. Fuels Lubr.* 1 (1) (2009) 505–519.

[5] J. Hult, S. Mayer, *Meas. Sci. Technol.* 24 (4) (2013) 045204.

[6] R. Wellander, J. Rosell, M. Richter, M. Alden, O. Andersson, B. Johansson, J. Duong, J. Hyvonen, *SAE Int. J. Engines* 7 (2) (2014) 928–936.

[7] D. Bensing, *Aufbau eines optisch zugänglichen Einzylinder-Viertaktmotors und charakterisierende Messungen*, Dissertation, Universität Duisburg-Essen, 2013.

[8] F. Unfug, *Experimentelle und numerische Untersuchung der Verbrennung eines mittelschnelllaufenden 4-Takt Dieselmotors*, Dissertation, Bd. 2013,7, Logos Berlin, Berlin, 2013.

[9] J. Duong, *Combustion Visualization in a Large Bore Gas Engine*, Thesis for the Degree of Licentiate in Engineering, Lund University, Lund, 2013.

[10] C. Disch, U. Waldenmaier, *High-Speed Flame Chemiluminescence Investigations of Prechamber Jets in a Lean Mixture Large-Bore Natural Gas Engine*, 2013.

[11] S. Mayer, J. Hult, K.J. Nogenmyr, S. Clausen (Eds.), *Advanced optical development tools for two-stroke marine diesel engines*, CONSEIL INTERNATIONAL.

[12] S. Mayer (Ed.), *IN-SITU OPTICAL COMBUSTION DIAGNOSTICS ON A LARGE TWO-STROKE MARINE DIESEL ENGINE*, Bergen, 2010.

[13] B. Korb, S. Gleis, in: *Conference proceedings / Die Fachkonferenz zur Numerischen Simulation*, CADFEM GmbH, Grafing bei München, Darmstadt, 2015.

[14] M. Jakob, *Optical Investigation of Diesel-Engine Related Combustion Processes*, Dissertation, Rheinisch-Westfälische Technische Hochschule, Aachen, 2014.

[15] E.A. Greis, *Laseroptische Untersuchungen des Verbrennungsprozesses in einem PKW-Dieselmotor*, Dissertation, Rheinisch-Westfälische Technische Hochschule, Aachen, 2007.

[16] P. Hügel, C. Disch, S. Palaveev, H. Kubach, Ulrich Spicher, J. Pfeil, B. Dirumdam (Eds.), *Optische Untersuchungen der Vorkammer- Fackelstrahlen und der Flammenausbreitung mit High-Speed-Kamera und Lichtleiter-Messtechnik an einem Gas-Großmotor*, Dessauer Gasmotoren-Konferenz, 21-22 March, 2013.

[17] Heidelinde Holzer, Jörg Reissing, Franz-Xaver biermeir, Wolfgang Nehse, Markus Braunsperger, Harald Philip, Erich Keiz.

[18] M. Epp, *Optische Untersuchungen einer Einspritzstrategie mit früher Voreinspritzung an einem schweröltauglichen mittelschnelllaufenden Commen Rail-Großdieselmotor*, Dissertation, Universität Rostock, Rostock, 2013.

[19] *Optical and Numerical Investigation of the Combustion Process in a Single Cylinder Medium Speed Diesel Engine*, Bergen, 2010.

[20] F.W. Bowditch (1961).

[21] R. Wellander, *Multi-Dimensional Quantitative Laser-based Diagnostics Development and Practial Applications*, Doctoral Thesis, Lund University, Sweden, 2014.

[22] J. Nygren, J. Hult, M. Richter, M. Aldén, M. Christensen, A. Hultqvist, B. Johansson, *Proceedings of the Combustion Institute* 29 (1) (2002) 679–685.

[23] J. Hult, M. Richter, J. Nygren, M. Aldén, A. Hultqvist, M. Christensen, B. Johansson, *Applied optics* 41 (24) (2002) 5002–5014.

[24] A. Hultqvist, M. Christensen, B. Johansson, M. Richter, J. Nygren, J. Hult, M. Aldjn, in: *SAE 2002 World Congress & Exhibition*, MAR. 04, 2002, SAE International400 Commonwealth Drive, Warrendale, PA, United States, 2002.

[25] C.F. Kaminski, J. Hult, M. Richter, J. Nygren, A. Franke, M. Aldén, S. Lindenmaier, A. Dreizler, U. Maas, R.B. Williams, in: *International Fuels & Lubricants Meeting & Exposition*, OCT. 16, 2000, SAE International400 Commonwealth Drive, Warrendale, PA, United States, 2000.

[26] K. Kohse-Höinghaus, J.B. Jeffries (Eds.), *APPLIED COMBUSTION DIAGNOSTICS*, Taylor & Francis, New York, 2002.

[27] K. Kohse-Höinghaus, *Progress in Energy and Combustion Science* 20 (3) (1994) 203–279.

[28] C. Schulz, V. Sick, *Progress in Energy and Combustion Science* 31 (1) (2005) 75–121.

[29] C. Schulz, *Zeitschrift für Physikalische Chemie* 219 (5-2005) (2005) 509–554.

[30] H. Zhao, N. Ladommatos, *Progress in Energy and Combustion Science* 24 (4) (1998) 297–336.

[31] A.C. Eckbreth, P.A. Bonczyk, J.F. Verdieck, *Progress in Energy and Combustion Science* (Vol. 5) (1979) 253–322.

[32] J.W. Daily, *Progress in Energy and Combustion Science* 23 (2) (1997) 133–199.

[33] J. Eichler, H.-J. Eichler, *Laser: Bauformen, Strahlführung, Anwendungen mit 57 Tabellen, 164 Aufgaben und vollständigen Lösungswegen*, 6th ed., Springer, Berlin [u.a.], 2006.

[34] S. Einecke, C. Schulz, V. Sick, *Appl Phys B* 71 (5) (2000) 717–723.

[35] S. Faust, *Characterisation of organic fuel tracers for laser-based quantitative diagnostics of fuel concentration, temperature, and equivalence ratio in practical combustion processes*, Dissertation, Universität Duisburg-Essen, Duisburg-Essen, 2013.

[36] T. Blotevogel, M. Hartmann, H. Rottengruber, A. Leipertz, *Applied optics* 47 (35) (2008) 6488–6496.

[37] J. Reboux, D. Puechberty, F. Dionnet, in: *International Fuels & Lubricants Meeting & Exposition*, OCT. 17, 1994, SAE International400 Commonwealth Drive, Warrendale, PA, United States, 1994.

[38] W. Koban, J.D. Koch, R.K. Hanson, C. Schulz, *Appl Phys B* 80 (6) (2005) 777–784.

[39] W. Koban, J.D. Koch, V. Sick, N. Wermuth, R.K. Hanson, C. Schulz, *Proceedings of the Combustion Institute* 30 (1) (2005) 1545–1553.

[40] W. Koban, J.D. Koch, R.K. Hanson, C. Schulz, *Appl Phys B* 80 (2) (2005) 147–150.

[41] D. Frieden, V. Sick, J. Gronki, C. Schulz, *Appl Phys B* 75 (1) (2002) 137–141.

[42] W. Koban, J. Schorr, C. Schulz, *Applied Physics B: Lasers and Optics* 74 (1) (2002) 111–114.

[43] J. Kazenwadel, W. Koban, T. Kunzelmann, C. Schulz, *Chemical Physics Letters* 345 (3-4) (2001) 259–264.

[44] M. Richter, B. Axelsson, K. Nyholm, M. Aldén, *Symposium (International) on Combustion* 27 (1) (1998) 51–57.

[45] S. Lind, J. Trost, L. Zigan, A. Leipertz, S. Will, *Proceedings of the Combustion Institute* 35 (3) (2015) 3783–3791.

[46] R. Devillers, G. Bruneaux, C. Schulz, *Appl Phys B* 96 (4) (2009) 735–739.

[47] J. Koch, *Fuel Tracer Photophysics for quantitative planar laser-induced fluorescence*, 2005.

[48] Susanne Lind, Johannes Trost, Lars Zigan, Alfred Leipertz, Stefan Will (Eds.), *Application of multi-parameter laser-induced fluorescence with amine/ketone tracer mixtures in DISI engines*, 17th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 07-10 July, 2014.

[49] W. Kirchweger, R. Haslacher, *Brennverfahrensentwicklung für Erdgas-DI Motoren mittels Lasermessverfahren*, Institut für Verbrennungskraftmaschinen und Thermodynamik.

[50] R. Haslacher, C. Skalla, T. Jauk, H. Eichlseder (Eds.), *Application of Optical Measurement Methods for the Development of Combustion Processes with Hydrogen-Natural Gas-Mixtures*, DESSAUER GASMOTOREN-KONFERENZ.

[51] K.H. Tran, C. Morin, M. Kühni, P. Guibert, *Appl Phys B* 115 (4) (2014) 461–470.

[52] G. Grünefeld, M. Schütte, P. Andresen, *Applied Physics B: Lasers and Optics* 70 (2) (2000) 309–313.

[53] Hobbs, Philip C. D, *Building electro-optical systems: Making it all work*, 2nd ed., Wiley, Hoboken, N.J., 2009.

[54] J. Hult, S. Mayer, *Meas. Sci. Technol.* 22 (11) (2011) 115305.

[55] P. Petersson, R. Wellander, J. Olofsson, H. Carlsson, C. Carlsson, B.B. Watz, N. Boetkjaer, M. Richter, Aldén, L. Fuchs, X.-S. Bai (Eds.), *Simultaneous high-speed PIV and OH PLIF measurements and modal analysis for investigating flame-flow interaction in a low swirl flame*, 16th Int Symp on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 09-12 July, 2012.

[56] J. Olofsson, *Laser Diagnostic Techniques with Ultra-High Repetition Rate for Studies in Combustion Environments*, Doctoral Thesis, Lund University, Sweden, Division of Combustion Physics, 2007.

[57] J. Olofsson, M. Richter, M. Aldén, M. Augé, *Rev. Sci. Instrum.* 77 (1) (2006) 013104.

[58] J. Hult, A. Harvey, C.F. Kaminski (2003).

[59] B. Thurow, N. Jiang, W. Lempert, *Meas. Sci. Technol.* 24 (1) (2013) 012002.

[60] R. Wellander, M. Richter, M. Aldén, *Exp Fluids* 55 (6) (2014).