Laser Ignition in Internal Combustion Engines - A Contribution to a Sustainable Environment

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Abstract

Sustainability with regard to internal combustion engines is strongly linked to the fuels burnt and the overall efficiency. Laser ignition can enhance the combustion process and minimize pollutant formation. This paper is on laser ignition of sustainable fuels for future internal combustion engines.

Ignition is the process of starting radical reactions until a self-sustaining flame has developed. In technical appliances such as internal combustion engines, reliable ignition is necessary for adequate system performance. Ignition strongly affects the formation of pollutants and the extent of fuel conversion. This paper presents experimental results on laser-induced ignition for technical applications.

Laser ignition tests were performed with the fuels hydrogen and biogas in a static combustion cell and with gasoline in a spray-guided internal combustion engine. A Nd:YAG laser with 6 ns pulse duration, 1064 nm wavelength and 1-50 mJ pulse energy was used to ignite the fuel/air mixtures at initial pressures of 1-3 MPa. Schlieren photography was used for optical diagnostics of flame kernel development and shock wave propagation.

Compared to a conventional spark plug, a laser ignition system should be a favorable ignition source in terms of lean burn characteristics and system flexibility. Yet several problems remain unsolved, e.g. cost issues and the stability of the optical window. The literature does not reveal much information on this crucial system part. Different window configurations in engine test runs are compared and discussed.

Keywords: Laser ignition, spray-guided combustion, homogeneous combustion, high pressure, hydrogen, biogas, gasoline.

1 Introduction

Internal combustion engines play a dominant role in transportation and energy production. Even a slight improvement will translate into considerable reductions in pollutant emissions and impact on the environment.

The two major types of internal combustion engines are the Otto and the Diesel engine. The former relies on an ignition source to start combustion, the latter works in autoignition mode.

Ignition **[1]** is a complex phenomonon known to strongly affect the subsequent combustion. It is especially the early stages that have strong implications on pollutant formation, flame propagation and quenching.

The spark ignited Otto engine has a widespread use and has been subject to continuous, sophisticated improvements. The ignition source, however, changed little in the last 100 years. An electrical spark plug essentially consists of two electrodes with a gap in between where, upon application of a high voltage, an electrical breakthrough occurs.

A laser based ignition source, i.e. replacing the spark plug by the focused beam of a pulsed laser, has been envisaged for some time **[2]**. Also, it was tried to control autoignition by a laser light source **[3].**

The time scale of a laser-induced spark is by several orders of magnitude smaller than the time scales of turbulence and chemical kinetics. In **[4]**, the importance of the spark time scale on the flame kernel size and NO_x production is identified.

As it will be outlined in this paper, a laser ignition source has the potential of improving engine combustion with respect to conventional spark plugs.

1.1 Alternative ignition systems

The protection of the resources and the reduction of the CO_2 emissions with the aim to limit the greenhouse effect require a lowering of the fuel consumption of motor vehicles. Great importance for the reduction lies upon the driving source. Equally important are the optimization of the vehicle by the means of a reduction of the running resistance as well as a low-consumption arrangement of the entire powertrain system.

The most important contribution for lower fuel consumption lies in the spark ignition (SI) engine sector, due to the outstanding thermodynamic potential which the direct fuel injection provides.

Wall- and air-guided combustion processes already found their way into standard-production application and serial development, whereas quite some fundamental engineering work is still needed for combustion processes of the second generation. Problems occur primarily due to the fact that with conventional spark ignition the place of ignition cannot be specifically chosen, due to several reasons. By the means of laser induced ignition these difficulties can be reduced significantly.

The combination of technologies (spray-guided combustion process and laser induced ignition) seems to become of particular interest, since the ignition in the fuel spray is direct and thus the combustion initiation is secure and non-wearing.

The engine tests in this paper are on laser ignited, spray-guided combustion.

Another approach is laser ignition of a homogeneous mixture. Within the scope of this paper, laser ignition in homogeneous fuel/air mixtures was investigated in a combustion bomb without turbulence.

In **[4]**, other alternative ignition systems than laser ignition are reviewed. Laser ignition, microwave ignition, high frequency ignition are among the concepts widely investigated.

In this article the basics of applied laser ignition, will be illustrated and it potential compared to a conventional ignition system.

1.2 Laser ignition

Laser ignition, or laser-induced ignition, is the process of starting combustion by the stimulus of a laser light source.

Basically, energetic interactions of a laser with a gas may be classified into one of the following four schemes as described in **[5]**:

- thermal breakdown
- non-resonant breakdown
- resonant breakdown
- photochemical mechanisms

In the case of thermal interaction, ignition occurs without the generation of an electrical breakdown in the combustible medium. The ignition energy is absorbed by the gas mixture through vibrational or rotational modes of the molecules; therefore no well-localized ignition source exists. Instead, energy deposition occurs along the whole beam path in the gas. According to the characteristic transport times therein, it is not necessary to deposit the needed ignition energy in a very short time (pulse). So, this ignition process can also be achieved using quasi continuous wave (cw) lasers.

Another type, resonant breakdown, involves non-resonant multi-photon dissociation of a molecule followed by resonant photo ionization of an atom. As well as photochemical ignition, it requires highly energetic photons (UV to deep UV region). Therefore, these two types of interaction do not appear to be relevant for this study and practical applications.

In these experiments, the laser spark was created by a non-resonant breakdown. By focusing a pulsed laser to a sufficiently small spot size, the laser beam creates a high intensity and high electric fields in the focal region. This results in a well localised plasma with temperatures in the order of 10^6 K and pressures in the order of 10^2 MPa as mentioned in **[6,7].**

The most dominant plasma producing process is the electron cascade process: Initial electrons absorb photons out of the laser beam via the inverse bremsstrahlung process. If the electrons gain sufficient energy, they can ionise other gas molecules on impact, leading to an electron cascade and breakdown of the gas in the focal region. It is important to note that this process requires initial seed electrons. These electrons are produced from impurities in the gas mixture (dust, aerosols and soot particles) which are always present**.** These impurities absorb the laser radiation and lead to high local temperature and in consequence to free electrons starting the avalanche process. In contrast to multiphoton ionisation (MPI), no wavelength dependence is expected for this initiation path. It is very unlikely that the first free electrons are produced by multiphoton ionisation because the intensities in the focus (10^{10} W/mm^2) are too low to ionise gas molecules via this process, which requires intensities of more than 10^{12} W/mm^2 **[7,9].**

An overview of the processes involved in laser-induced ignition covering several orders of magnitude in time is shown in Fig. 1. Laser ignition encompasses the nanosecond domain of the laser pulse itself to the duration of the entire combustion lasting several hundreds of milliseconds. The laser energy is deposited in a few nanoseconds which leads to a shock wave generation. In the first milliseconds an ignition delay can be observed which has a duration between 5 – 100 ms depending on the mixture. Combustion can last between 100 ms up to several seconds again depending on the gas mixture, initial pressure, pulse energy, plasma size, position of the plasma in the combustion bomb and initial temperature.

Below the main advantages of laser ignition are given:

- a choice of arbitrary positioning of the ignition plasma in the combustion cylinder
- absence of quenching effects by the spark plug electrodes
- ignition of leaner mixtures than with the spark plug **[10]** => lower combustion temperatures => less NO_x emissions **[10,11]**

- no erosion effects as in the case of the spark plugs => lifetime of a laser ignition system expected to be significantly longer than that of a spark plug
- high load/ignition pressures possible => increase in efficiency
- precise ignition timing possible
- exact regulation of the ignition energy deposited in the ignition plasma
- easier possibility of multipoint ignition **[12-14]**
- shorter ignition delay time and shorter combustion time **[10, 15-17]**
- fuel-lean ignition possible

The disadvantages of laser ignition are:

- high system costs
- concept proven, but no commercial system available yet.

2 Experimental

This section describes the experimental setup. Laser ignition experiments were carried out in a constant volume vessel (0.9 l) and an internal combustion engine.

The constant volume vessel, also termed the combustion bomb, was used to conduct basic studies of laser ignition in homogeneous fuel/air mixtures. The sustainable fuels hydrogen and biogas were used. The biogas was obtained from a municipal water purification plant. It was composed of 50.5% CH_4, 31.7% CO_2 and 80 ppm H_2S.
Schlieren photography was used for accompanying optical diagnostics.

The engine, a one-cylinder research engine, was deployed for the investigation of spray-guided combustion initiated by a laser. Gasoline was used as a fuel here. The focus of sustainability is on laser ignition for enhanced combustion and efficiency.

2.1 Laser ignition and concurrent Schlieren photography in a combustion bomb

The laser ignition experiments in the constant volume vessel were carried out with hydrogen and biogas. The experimental setup and tests with methane are outlined in **[2].**
A pulsed Nd:YAG laser with pulse energies from 1 to 50 mJ was used for the ignition tests. Table 1 lists the specifications of the laser.
Schlieren photography was conducted in the plane of the focal spot of the igniting laser. Perpendicularly to the igniting laser beam, a collimated light beam from a flash lamp (1 µs pulse duration) was shone through the combustion vessel. As the diffraction index of light depends on the type and mass density of a gas, areas with different temperatures or different pressures have different diffraction indices. So a parallel beam of light is diffracted at differences of temperature and pressure and the diffraction angle is proportional to the first derivate of these parameters **[18].** The experimental setup for the Schlieren experiments is outlined in **[19].**

2.2 Laser ignition in an internal combustion engine

A one-cylinder research engine was used as a test engine. The research engine was equipped with a four-valve DOHC cylinder head with a spray-guided combustion system of AVL List GmbH **[20]**. In a double-overhead-camshaft (DOHC) layout, one camshaft actuates the intake valves, and one camshaft operates the exhaust valves. Gasoline was used as a fuel. The same laser as in the combustion bomb tests in 2.1 was used (see Table 1).
In Table 2 the key technical data of the test engine are listed.

Engine test runs were carried out with two different approaches.

First, a plane window was inserted into the cylinder head of the engine. A focusing lens was placed in front of that window in order to focus the laser beam down into the combustion bomb (“separated optics”).

Second, a more sophisticated window was deployed. A lens-like curvature was engraved directly into the window. By using such a special window, no further lens was required (“combined optics”).

This is depicted schematically in Fig. 2.

3 Results and discussion

3.1.1. Laser ignition of hydrogen/air mixtures

Fig. 3 depicts a pressure history of combustions for different mixtures (λ) at an initial chamber temperature of 473 K and an initial pressure of 1 MPa. Comparable pressure histories could be seen for higher initial pressures. λ is the so called air/fuel equivalence ratio: $\lambda < 1$ signifies a fuel-rich mixture, whereas $\lambda > 1$ describes a fuel-lean mixture.

Between $\lambda = 2.5$ and 3.6 (14.4% and 10.4% H_2) an oscillating pressure history could be observed having a frequency in the lower kHz region which is the resonant frequency of the combustion bomb **[11].** The oscillating combustion process is called knocking, which means that the combustion propagates not only by a spherical flame front, starting from the plasma but also that the mixture explodes at different locations in the end-gas (unburned gas) as an effect of self ignition conditions **[11].** With “rich” hydrogen-air mixtures ($\lambda < 3.6$) the flame propagates at a specific instant during the combustion time with sonic velocity through the gas and produces high pressure and temperature values in the end-gas region leading to auto ignition **[11]**. This auto ignition process produces shock waves which are reflected from the chamber walls and end in oscillations which can be observed in Fig. 3 for a λ between 2 and 3.6. Knocking is very disadvantageous for engine applications.

Pressure histories for a constant gas mixture ($\lambda = 3.5$) and constant initial temperature ($T = 473$ K) but different initial filling pressures are plotted in Fig. 4. The main result of this diagram is that with higher initial pressures the minimum pulse energy for ignition (MPE) is decreasing like it was observed for methane-air mixtures in **[2,6,9,10].** Further on, it can be seen that with higher initial pressures, which means higher energy contents in the combustion bomb , the peak pressures increases. Gas mixtures with $\lambda = 3.5$ represent the leaner boundary where knocking starts, as depicted in Fig. 4. Especially at this boundary knocking occurred only at lower filling pressures. With higher initial filling pressures no knocking could be observed. Richer gas mixtures only have a knocking combustion with no dependency on the filling pressure.

3.1.2. Laser ignition of biogas/air mixtures

Biogas is CO_2-neutral and can act as a promising alternative fuel having a high availability. The two most common sources of biogas are digester gas and landfill gas. Bacteria form biogas during anaerobic fermentation of organic matters. The degradation is a very complex process and requires certain environmental conditions. Biogas is primarily composed of CH_4 (50-70%) and CO_2 (25-50%). Digester gas is produced at sewage plants during treatment of municipal and industrial sewage. Landfill gas is obtained during decomposition of organic waste in sanitary landfills. When using biogas as fuel one must also pay attention to several harmful ingredients such as H_2S polluting e.g. the catalytic converter of the engine or blocking the window of the laser (see later for issues related to the window).

With respect to laser ignition, biogas was compared to methane.

The investigated methane/air and biogas/air mixtures contained similar methane concentrations but in the case of biogas additionally CO_2 was present.

Fuel-lean biogas/air mixtures exhibit a slower combustion process resulting in lower peak pressure and flame emission compared to methane-air mixtures of similar air to fuel equivalence ratio.

The reason for these results could be due to the presence of CO_2 in the biogas which reduces the burning velocity due to obstructing the flame propagation during combustion. SO_2 may also be responsible for the decreased burning rate of the biogas/air mixtures reducing mainly the O-radical concentration to equilibrium state due to the recombination of the O-radicals **[21]**. In Fig. 5, images of the developing flame kernel in laser ignited biogas/air mixtures are depicted (see below).

More details on laser ignition of biogas/air mixtures can be found in **[21]**.

3.1.3. Shockwave and flame kernel development by Schlieren photography

Schlieren photography was used to obtain visual information on the shock wave formation and flame kernel development.

Schlieren photography is an experimentally uncomplicated technique that has been applied successfully to the investigation of laser ignition, too.

However, the literature contains very scarce information on pressures higher than ambient. In this study, high pressure tests were done.

Fig. 5 shows Schlieren photographs of laser ignition test runs. In all images, the laser enters from the left side. The images are 11.6 mm long and 9.15 mm high.

In the top row, images of the laser-induced spark and shock wave in pure air at 25 bar can be seen.

In the middle row, consecutives images of laser-ignition of H_2/air mixtures at 25 bar and lambda 6.0 are shown.

The bottom row shows Schlieren images of laser-ignition of biogas/air mixtures at 25 bar and lambda 1.8.

The shock wave carries two major implications on laser ignition: First, it transports energy away from the ignition spot. Second, it causes a significant temperature rise.

When the shock wave has detached from the hot core air, both phenomena can be studied independently. The shock wave initially has an ellipsoidal shape caused by the asymmetric energy deposition of the laser.

Results and trends from the literature, predominantly existing in the ambient pressure regime, could be verified using Schlieren photography.

More information on Schlieren photography of laser ignition can be found in **[19].**

3.2 Engine tests

Engine tests were conducted to investigate the optical window with respect to

- Durability of the optics (vibrations)
- Minimum ignition energy
- Wear and fouling properties of the inner window surface

The engine tests were conducted with gasoline. Whereas the focus of the previous tests and ongoing work in a static combustion bomb was on the understanding of the ignition process, the aim of the engine tests was to investigate the durability of the optical window.

3.2.1 Optics deposits and self-cleaning effect

As stated above, laser ignition is based on the principle of optical breakdown and thus it is essential to provide the necessary intensity which is approximately 10^{11} W/cm^2 in the focus. The energy emitted from the laser is attenuated by reflections on the surface of the window and the lens and by absorption in the lens, in the combustion-chamber window and in the deposits on the windows. The transmission of typical windows in the infrared is approximately 90%; the reflections on the surfaces further reduce the energy. Adding it up, when the laser beam passes through a window or a lens, the losses amount to approximately 15%.

The laser self-cleaning effect was studied with deposits from the "true" combustion process (3.2.2), and also with artificially applied deposits (3.2.3).

3.2.2 Laser self-cleaning with deposits caused by the combustion process

Fig. 6 shows the cold start performance of the engine with a soiled window. Here, the deposits stemmed from a real combustion process inside the engine (see **[22]** for details).

These deposits, which were caused by the combustion process, were built up during the tests with a conventional spark plug. Thereby the combustion-chamber window was installed in different load points, the engine running mode being homogeneous, for about 20 hours. As it can be seen in Fig. 6, the window was soiled with a dark and opaque layer of combustion deposits after these 20 hours.

In the simulated cold-start test with a stratified engine running mode with 1000 rpm (rotations per minute) and p_{MEP} = 1 bar, the p_{MEP} course was recorded for each cycle, as shown in Fig. 6 (MEP = mean effective pressure). The first ignition and injection impulse occurred at cycle 10.

The first laser impulse already ignites the mixture. The following ignition impulses resulted in a running without misfire. After the test (100 cycles) the window was disassembled and, as visible in Fig. 6, all deposits were removed in the beam passage area.

3.2.3 Laser self-cleaning with "worst case" deposits

In order to study the effect of the laser on a heavily soiled window, it was chosen to artificially apply a layer of dirt onto the window.

This artificially applied soiling on the combustion-chamber side of the window represents a kind of "worst case scenario".

For doing so, a mixture of Diesel soot and waste oil at a ratio of 1:5 was produced and, with a thickness of 1 mm, applied to the combustion-chamber window and afterwards dried.

Fig. 7 shows the clear influence of the laser energy on the self-cleaning effect of the optics. Up to a build-up energy of the threshold energy E_S, an engine operation without misfire is possible with a separated optics configuration, presupposed that a corresponding pulse number for the burning-off of the window is shot. This build-up energy E_S is significantly higher in combined optics when aiming to reach a misfire rate of 0%. The relative laser energy was replaced by the actually occurring relative energy intensity I on the combustion-chamber side of the window in Fig. 8.

An engine operation without misfire with both optics configurations, i.e. separated and combined optics (see Fig. 2), is possible as of a build-up intensity of I_S. In separated optics this build-up intensity I_S corresponds to the build-up energy of E_S.

However, the minimum intensity for keeping the combustions-chamber window clean during the engine running is $I_S/2$.

The minimum ignition energy when the engine running is stationary is determined by the intensity level of self-cleaning at the optics, and not by the engine-related working process. In the whole engine operating map a secure ignition and self-cleaning of the optics can be guaranteed with the laser energy E_S.
For cold start applications, the laser energy should thus be raised momentarily in order to burn off possible deposits at the optics.

Fig. 9 shows the laser energy for the different window configurations (compare Fig. 2). Both the minimum ignition energy (left bar) and the laser energy for a 20 hour test run (right bar) are shown.
As it can be clearly seen, the combined optics are more favorable than the separated optics with respect to required laser energy.
The energy density at the window is a major criterion for the ablation of combustion bomb deposits.
During cold start, heating up and in the case of existing deposits only a high laser energy density can ensure the ablation effect at the location of the laser.
The energy density is therefore an important determinant on the reliability of a future laser ignition system.
As it can be seen from Fig. 10, the energy density is by an order of magnitude higher for the separated optics than for the combined optics for the chosen configuration.
The separated optics scheme leads to a higher energy density at the window. Especially in the case of cold start or unexpected deposits, this setup should be more reliable than the combined optics.

As can be seen from Fig.9 and Fig. 10, there is a trade-off between low laser energy requirements (combined optics) and system reliability (separated optics).
From an engine manufacturer’s point of view, system reliability comes first, which translates into higher required laser energies and hence higher system costs.

3.2.4 Properties of the optical window

Potential window materials evidently have to be transparent for the laser radiation. The laser used in these tests was a Nd:YAG laser at 1064 nm. The near infrared spectral region is a common wavelength region for laser suitable for laser ignition test runs. So infrared transparent windows are good candidates for a future laser ignition system.
The second, no less important prerequisite is that the window withstand the high energy density of the laser. The shorter the focal length of the lens, the higher generally the laser light intensity of the passing laser beam becomes at the window surface.
Third, the window must show a weak inclination to deposits and aid laser self-cleaning. Combustion bomb deposits can either be organic (up to 300°C) or inorganic in nature. When they form on the window, they increasingly block the incoming laser light up to a point where no breakdown can be produced any more. In **[16]**, for instance, laser ignition tests of methane/air mixtures in an engine had to be aborted after 1.25 hours because of excessive combustion product build-up. ZnSe was used in that study.
The formation of deposits on the window depends on the temperature, the fuel and the engine oil.

The laser light also interacts with deposits. By a process called laser cleaning or ablation **[23],** deposits are removed by the laser light. The contrary can also happen, i.e. that the laser fosters the formation of deposits at the location where it enters the combustion chamber.

Generally, ablation overweighs so that a kind of self-cleaning effect as shown above is achieved by the laser.

Sapphire, quartz and ZnSe are among potential window materials in a future laser ignited engine.

[24] reviews the major infrared transparent substrates suitable for window fabrication.

4 Conclusion

In this work, laser-induced ignition of hydrogen/air and biogas/air mixtures was investigated experimentally in a static combustion bomb. An enhanced ignition source can make a strong contribution to sustainability in internal combustion engines.

Schlieren photography was applied to gain information on the shock wave propagation and early flame kernel development.

Results and trends from the literature, predominantly existing in the ambient pressure regime, could be verified.

It was found for the laser ignition tests with hydrogen that with higher initial pressures the minimum pulse energy for ignition (MPE) decreases. That behaviour was also found for methane.

Fuel-lean biogas/air mixtures exhibit a slower combustion process resulting in lower peak pressure and flame emission compared to methane-air mixtures of similar air to fuel equivalence ratio.

The applicability of the laser induced ignition as a future ignition system for combustion engines with spray-guided combustion process could be proved with the basic research.

The lowest required ignition energy in a stationary engine running mode is defined by the intensity level of the self-cleaning effect at the optics and not by the engine-related working cycle.

In order to prevent deposits on the optics by the combustion process, a certain build-up intensity I_S has to be available on the combustion bomb side of the window in order to ensure an engine operation without misfire.

The energy intensity necessary to keep the burnt off optics clean during the normal engine operation is, however, lower. Half the build-up intensity I_S has proven to be sufficient in order to prevent deposits.

From the point of view of components development, the main goal is the creation of a laser system which meets the engine-specific requirements. Basically, it is possible to ignite mixtures with different laser systems. The concept with the greatest development potential regarding efficiency and miniaturization is the diode pumped solid-state laser.

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Figures

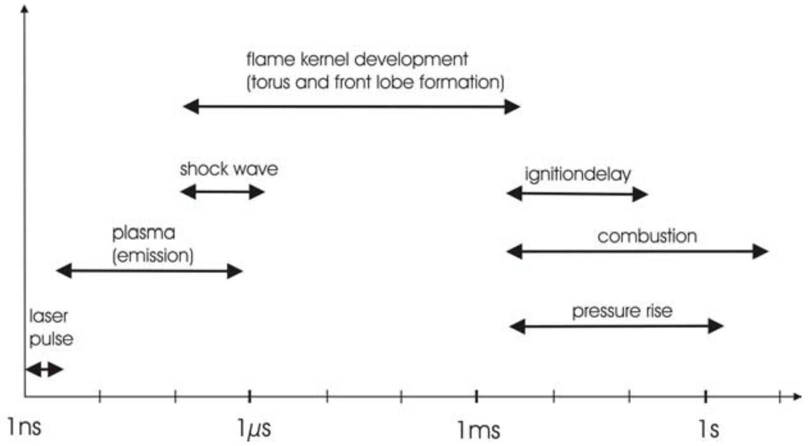


Fig. 1

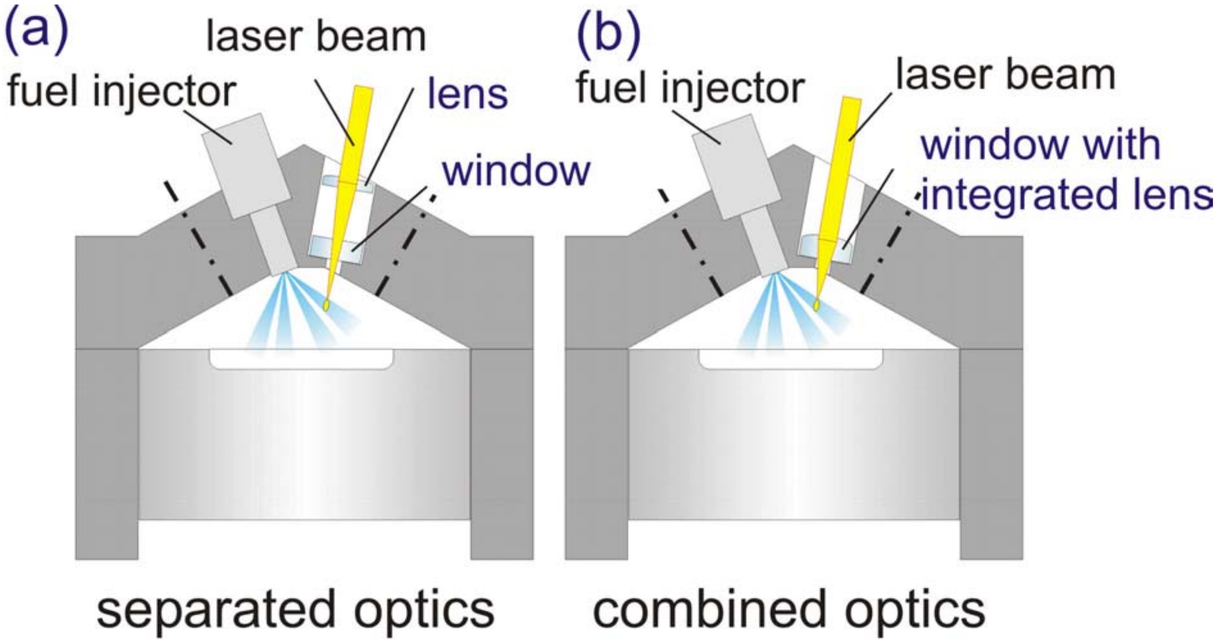
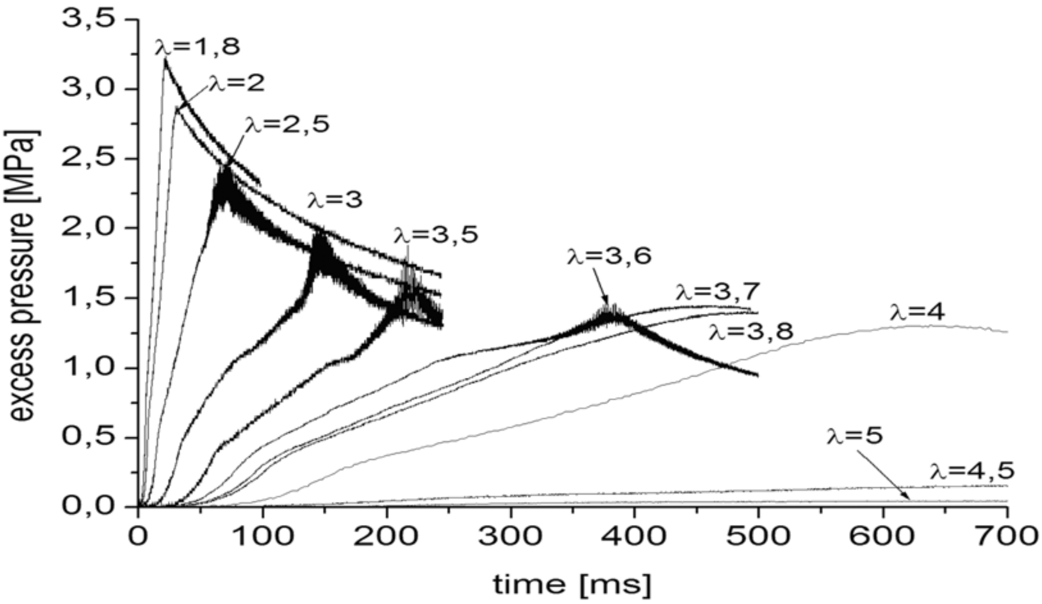


Fig. 2



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3,0
2,5
2,0
1,5
1,0
0,5
0,0
excess pressure [MPa]
λ=1,8
λ=2
λ=2,5
λ=3
λ=3,5
λ=3,6
λ=3,7
λ=3,8
λ=4
λ=5
λ=4,5
0
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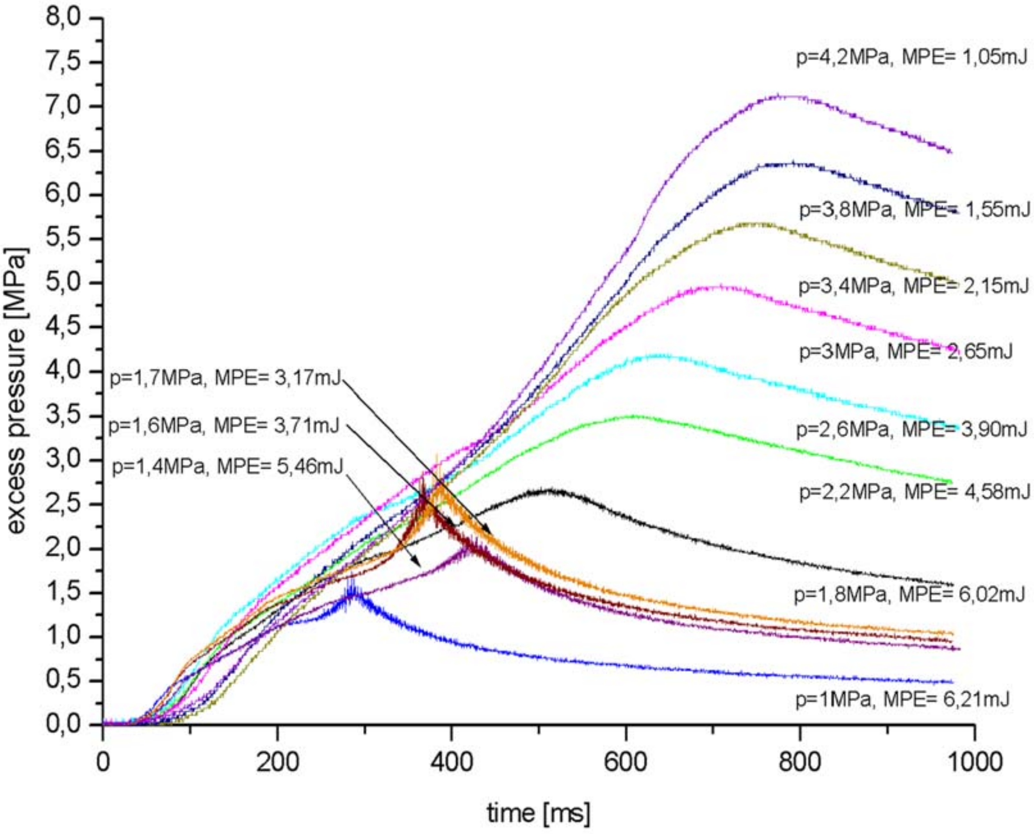
200
300
400
500
600
700
time [ms]

Fig. 3



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4,5
4,0
3,5
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2,0
1,5
1,0
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0,0
excess pressure [MPa]
p=4,2MPa, MPE= 1,05mJ
p=3,8MPa, MPE= 1,55mJ
p=3,4MPa, MPE= 2,15mJ
p=3MPa, MPE= 2,65mJ
p=2,6MPa, MPE= 3,90mJ
p=2,2MPa, MPE= 4,58mJ
p=1,8MPa, MPE= 6,02mJ
p=1MPa, MPE= 6,21mJ
p=1,7MPa, MPE= 3,17mJ
p=1,6MPa, MPE= 3,71mJ
p=1,4MPa, MPE= 5,46mJ
0
200
400
600
800
1000
time [ms]

Fig. 4

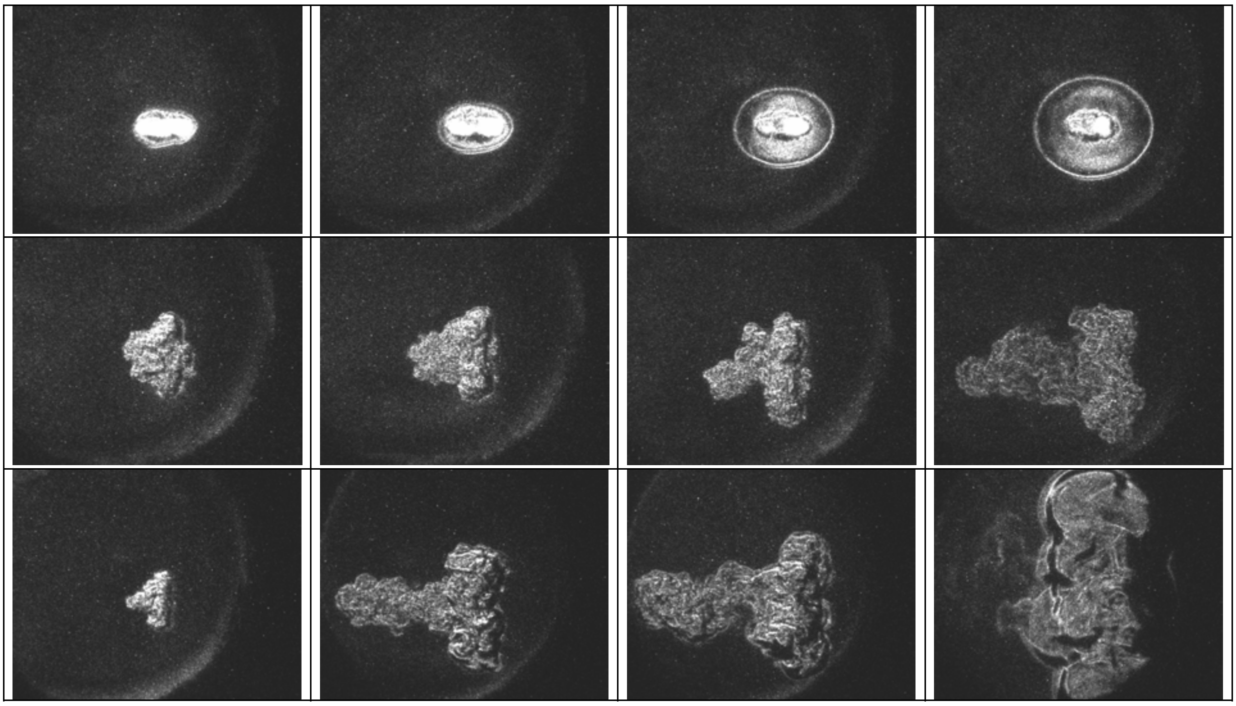

Fig. 5

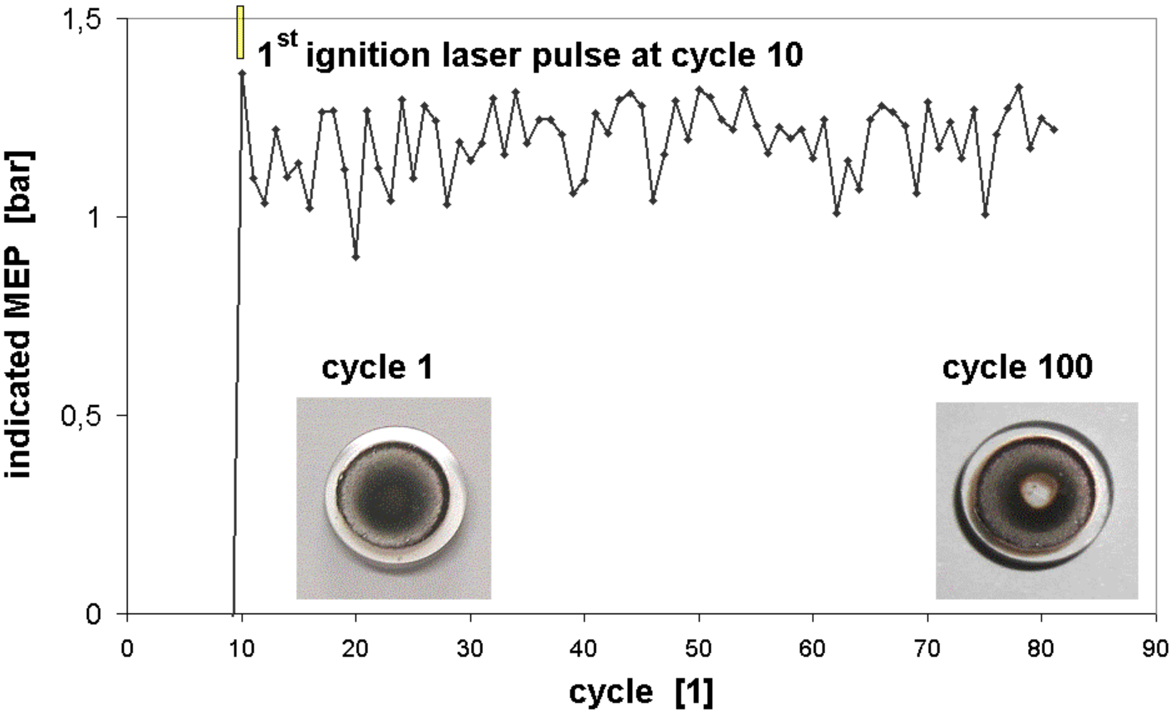
1st ignition laser pulse at cycle 10
indicated MEP [bar]
1,5
1
0,5
0
cycle 1
cycle 100
0
10
20
30
40
50
60
70
80
90
cycle [1]

Fig. 6

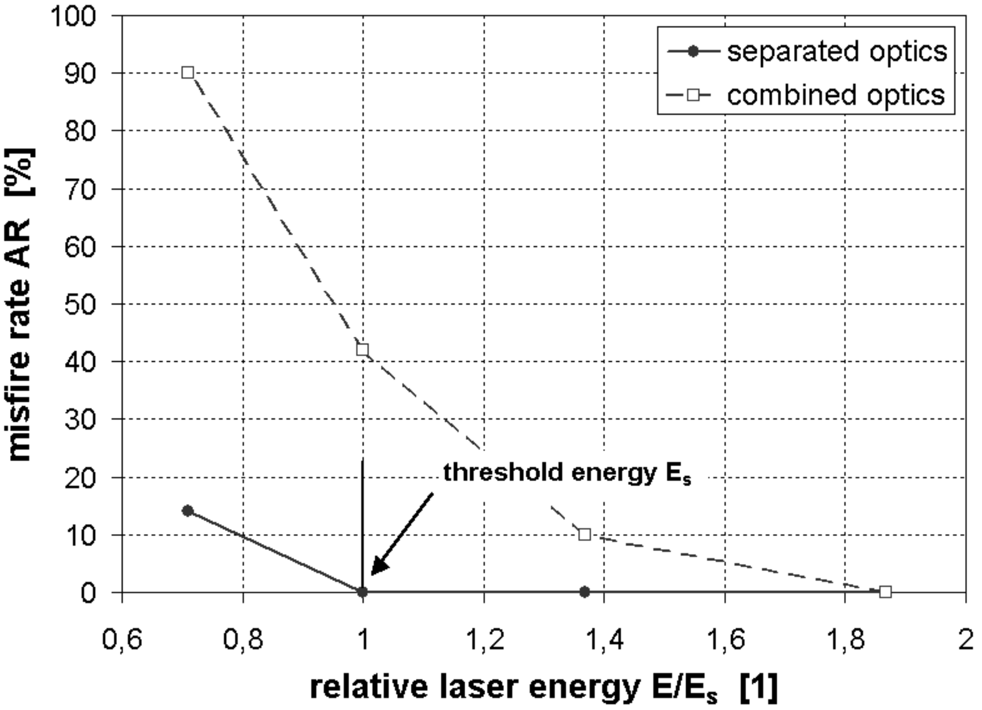
misfire rate AR [%]
relative laser energy E/E_s [1]
separated optics
combined optics
threshold energy E_s
100
90
80
70
60
50
40
30
20
10
0
0,6
0,8
1
1,2
1,4
1,6
1,8
2

Fig. 7

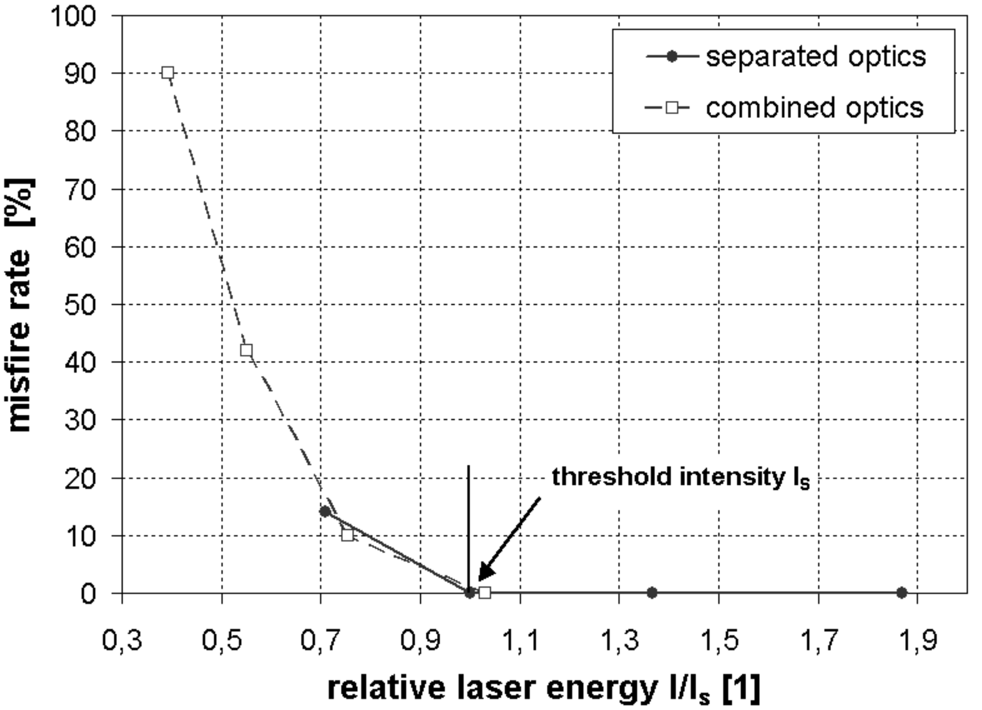
misfire rate [%]
relative laser energy I/I_s [1]
separated optics
combined optics
threshold intensity I_s
100
90
80
70
60
50
40
30
20
10
0
0,3
0,5
0,7
0,9
1,1
1,3
1,5
1,7
1,9

Fig. 8

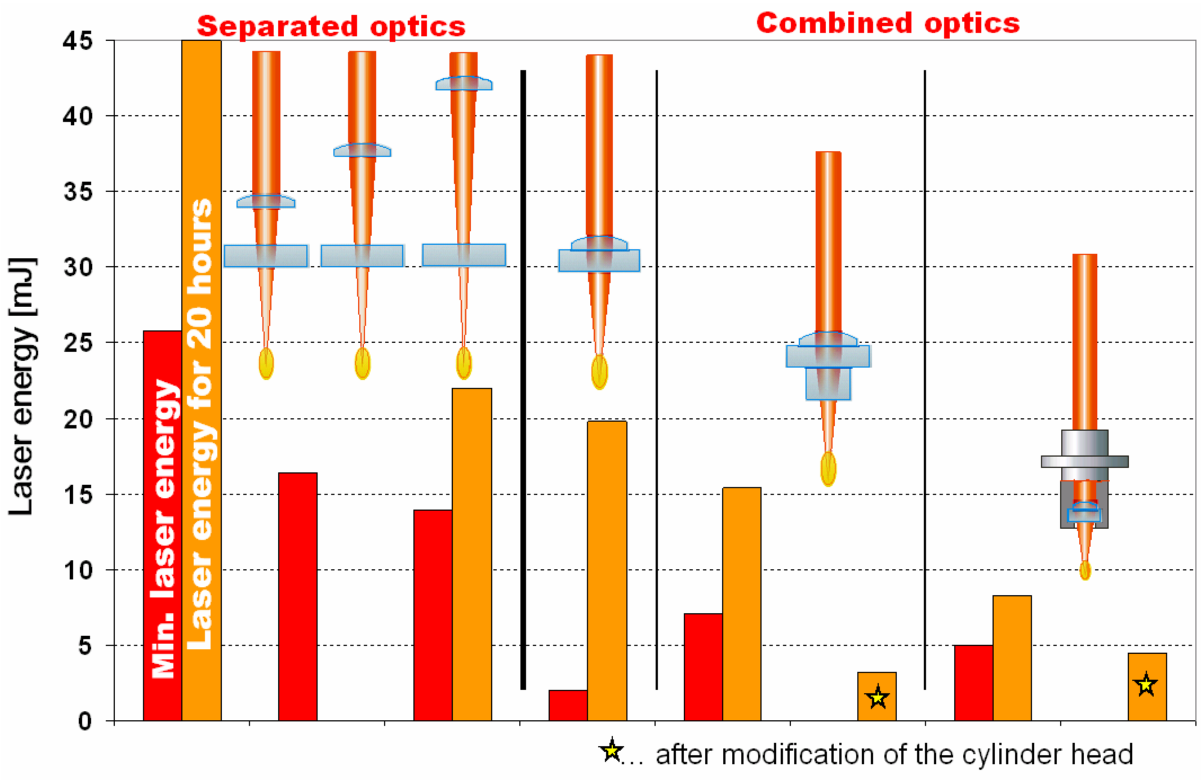
Separated optics
Combined optics
Laser energy [mJ]
45
40
35
30
25
20
15
10
5
0
Min. laser energy
Laser energy for 20 hours
☆... after modification of the cylinder head

Fig. 9

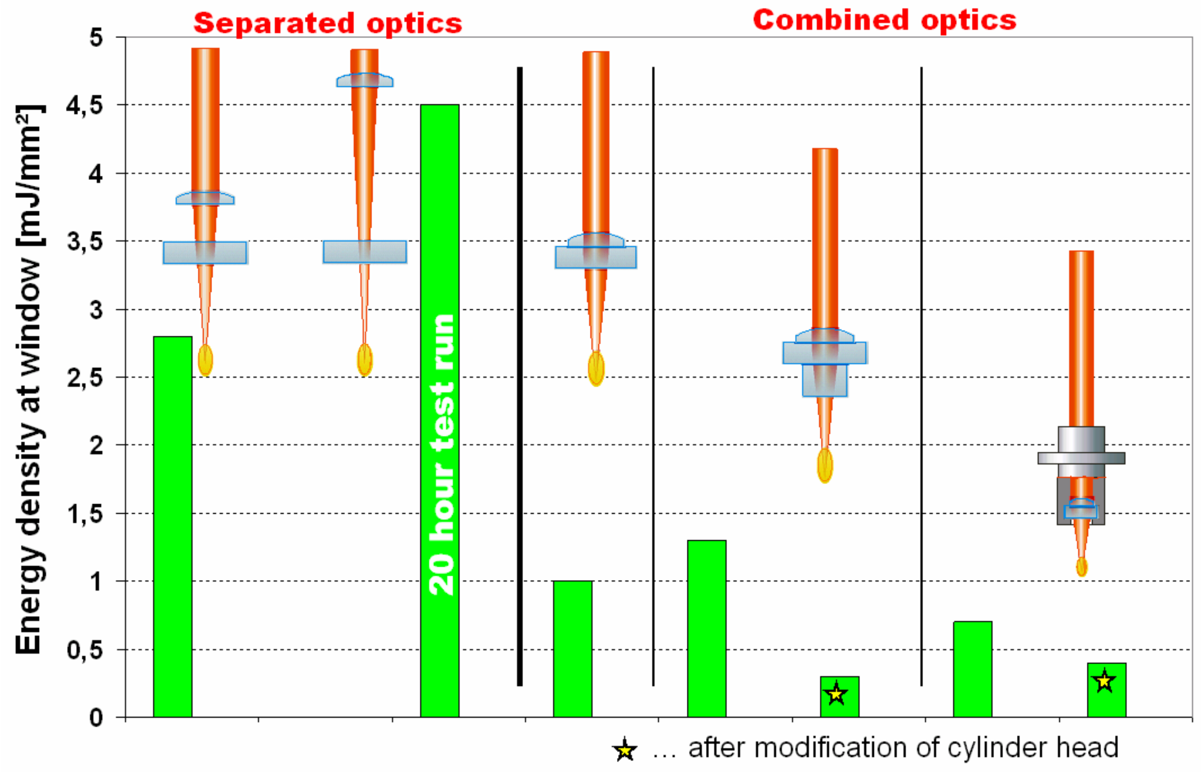
Separated optics
Combined optics
Energy density at window [mJ/mm²]
5
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
20 hour test run
☆ ... after modification of cylinder head

Fig. 10

One-cylinder research engine	
Four-valve cylinder head	
Spray-guided combustion process	
Multihole injector	
Stroke	85 mm
Bore	88 mm
Displacement volume	517 cm^3
Compression ratio ε	11.6

Table 1

Flash lamp pulsed Nd:YAG laser	
Manufacturer	Quantel S.A.
Type	Brilliant
Wavelength	1064 nm or 532 nm
Pulse energy	1-50 mJ
Pulse duration	6 ns
Max. beam performance	10 W
Power consumption	1 kW
Beam diameter	6 mm

Table 2

Figure captions

Fig 1: Scope of timescales of various processes involved in laser-induced ignition: The lengths of the double arrowed lines indicate the duration ranges of the indicated processes.

Fig. 2: Schematic cross section of the engine for laser ignition test runs. Two window/lens configurations were tested: Fig. 2(a) shows the separated optics, Fig. 2(b) the combined optics.

Fig. 3: Pressure history in the combustion bomb after ignition applying minimum pulse energy for ignition (MPE); $\lambda = 1.8 - 5$; initial temperature = 473 K, initial pressure = 1 MPa; If the air/fuel equivalence ratio (λ) is increasing (leaner mixtures), the peak pressure is decreasing but the total combustion time is increasing.

Fig. 4: Pressure history in the combustion bomb after ignition applying minimum pulse energy for ignition (MPE); $\lambda = 3.5$, initial temperature = 473 K, initial pressure = 1 – 4.2 MPa; For higher initial pressures the peak pressure, ignition delay and total combustion time is increasing but the minimum pulse energy for ignition (MPE) is decreasing.

Fig. 5: Schlieren photographs of laser ignition, laser entering from the left side. The images are 11.6 mm long and 9.15 mm high.
Top row: Laser-induced spark and shock wave in 25 bar air; From left to right: 500 ns, 1000 ns, 2000 ns, 3000 ns.
Middle row: Laser-ignition of H_2/air mixtures at 25 bar, lambda 6.0; From left to right: 100 µs, 200 µs, 300 µs, 1000 µs.
Bottom row: Laser-ignition of biogas/air mixtures at 25 bar, lambda 1.8; From left to right: 100 µs, 900 µs, 1800 µs, 15000 µs.

Fig. 6: Cold start performance with soiled combustion bomb window – deposits because of engine-related combustion process

Fig. 7: Misfire rate dependent on the relative laser energy in a simulated cold start test, comparison of the optics, worst case deposits

Fig. 8: Influence of the energy intensity I at the combustion bomb window on the burn off performance and the misfire rate, worst case deposits

Fig. 9: Laser energy for ignition as a function of different window configurations. The separated optics, i.e. a focusing lens before a window, is less favorable than a combined optics, i.e. a window with integrated lens curvature, with respect to the minimum ignition energy.

Fig. 10: Energy density at the window. It is higher for the separated optics. The higher the energy density, the better ablation works. The separated optics scheme should therefore be more reliable than the combined optics.

Table 1: Technical data of the laser. A solid-state laser was used here.

Table 2: Technical key data of the test engine. A spray-guided research engine running on gasoline was used.